BULLETIN OF THE UNIVERSITY OF WISCONSIN

NO. 450

ENGINEERING SERIES, VOL. 6, NO. 7, PP. 405–573

AN INVESTIGATION OF THE AIR LIFT PUMP

BY

GEO. JACOB DAVIS, JR., C. E.

Assistant Professor of Hydraulic Engineering

The University of Wisconsin

AND

CARL ROBERT WEIDNER, C. E.

Instructor in Hydraulic Engineering

The University of Wisconsin

RESEARCHES IN HYDRAULICS

DANIEL W. MEAD, PROFESSOR IN HYDRAULIC AND SANITARY ENGINEERING

MADISON, WISCONSIN

OCTOBER, 1911

PRICE 40 CENTS.

BULLETIN OF THE UNIVERSITY OF WISCONSIN

Entered as second-class matter June 10, 1898, at the post office at Madison, Wisconsin under the Act of July 16, 1894

The Bulletin of the University of Wisconsin is published bimonthly at Madison. For postal purposes, all issues in all series of the Bulletin are included in one consecutive numbering as published, a numbering which has no relation whatever to the arrangement in series and volumes.

The Economics and Political Science series, the History series, the Philology and Literature series, the Science series, the Engineering series, and the University extension series contain original papers by persons connected with the University. The series formerly issued as the Economics, Political Science, and History series was discontinued with the completion of the second volume and has been replaced by the Economics and Political Science series and the History series.

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CONTENTS

Wisconsin Experiments

ILLUSTRATIONS

LIST OF SYMBOLS

Areas

a_o = area of orifice in square feet.

a_p = area of eduction pipe in square feet.

Coefficients

c = coefficient of pipe friction and slip (variable).

c_e = coefficient of entrance.

c_o = coefficient of discharge of orifice.

c_p = coefficient of pipe friction and slip (average).

Efficiency

e = efficiency.

Distances

h = head.

h_a = head produced by the air used.

h_b = elevation of outlet above datum.

h_c = elevation of point C above datum.

h_e = head lost at entrance.

h_i = elevation of inlet above datum.

h_l = lift, in feet.

h_o = head lost due to elbow.

h_p = head lost in eduction pipe due to pipe friction and slip.

h_s = depth of submergence in feet.

Work

L = total work, per pound of air, in foot pounds.

l = work output, in foot gallons per second.

l_i = work input, in foot pounds per second.

l_m = maximum work output, in foot gallons per second.

l_o = work output, in foot pounds per second.

Pressures

p = absolute pressure at any point, with variable specific weight of air.

p_a = loss of pressure due to air friction, when discharging into the atmosphere.

p_b = barometric pressure, acting on the surface of the water in the well and also on the discharge end of the pipe A (Fig. 3).

p_c = absolute pressure at the point C (Fig. 3).

p_d = absolute pressure of air at down stream side of orifice, in pounds per square inch.

p_g = absolute pressure at gage.

p_i = absolute pressure at inlet in the foot-piece.

p_s = standard atmospheric pressure (=14.7 pounds per square inch).

p_u = absolute pressure of air at upstream side of orifice, in pounds per square inch.

p_x = loss of pressure due to air friction when discharging against the pressure p_i in the foot-piece.

p_1 = absolute initial pressure of air, in pounds per square foot.

p_2 = absolute final pressure of air, in pounds per square foot.

Volumes

Q_i = volume of air at pressure p_i, in cubic feet.

Q_s = volume of air at standard atmospheric pressure (14.7 pounds per square inch).

q_a = discharge of free air, in cubic feet per second.

q_b = discharge of air at pressure p_b.

q_g = discharge of water in gallons per minute.

q_w = discharge of water, in cubic feet per second.

q_x = volume of air at pressure p_i.

q_1 = volume of air at pressure p_1.

q_2 = volume of air at pressure p_2.

Submergence

s = percentage of submergence.

s_m = percentage of submergence corresponding to maximum discharge.

Temperature

T_u = absolute temperature at upstream side of orifice, in degrees Fahrenheit.

Densities

u = density of mixture of air and water, variable.

u_a = density of air at 14.7 pounds per square inch pressure.

u_b = density of air at the discharge end of the eduction pipe.

u_i = density of air at inlet in foot-piece.

u_v = density of air, variable.

u_w = density of fluid pumped.

r = the ratio of compression in atmospheres.

Velocities

v = variable velocity.

v_a = velocity of air in pipe, when discharging into the atmosphere.

v_b = velocity of the mixture of air and liquid, at the outlet of the eduction pipe, in feet per second.

v_c = velocity of water in the well outside of the eduction pipe at point c (Fig. 3).

v_i = velocity of the liquid in the eduction pipe below the air inlet.

v_t = velocity of the liquid in the tail-piece.

v_x = velocity of air in pipe, when discharging against pressure p_i.

Weights

w_a = weight of air used in pounds per second.

w_w = weight of water pumped in pounds per second.

INTRODUCTION

The air lift method of pumping, though not highly efficient as compared with some other methods, is nevertheless an important one, owing to the many advantages it possesses over other methods in the pumping of corrosive liquids, in pumping large quantities from wells of small bore, and on account of other features which will be discussed on a succeeding page.

Notwithstanding the fact that this method of raising liquids has been known for over a century and is now quite extensively used in both small and large pumping installations, the amount of reliable data, that are available to the practicing engineer, concerning the performance of this type of pump, is very meagre. Numerous tests of air lift pumps have been made by the manufacturers of air compressors and patented devices to be used in connection with air lift pumping plants, but the information gained from such tests has not been made public. The engineer in private practice has available, for use in designing, only the data from some tests on very small scale apparatus and those from a number of tests on actual installations, where it was not practicable to vary the conditions of operation much, nor to make accurate measurements of quantities.

With the purpose of supplying the demand for reliable data, from tests on pumps of commercial size and of various types, the investigations described and discussed in this bulletin were undertaken. The experiments, which comprise more than 600 runs, were carried on in the Hydraulic Laboratory of the University of Wisconsin. In taking the data on the first 318 runs the writers were assisted by B. R. McBride, then Instructor in Hydraulic Engineering, who supervised the work

of C. J. Miller and E. J. Springer, then senior students in the College of Engineering, who used the data taken by them as the basis of a thesis for the baccalaureate degree. Assistance in the way of computing, drafting, and changing apparatus, has also been given from time to time by E. P. Abbott, G. P. Stocker, M. C. Koenig, E. B. Nelson, P. C. Dodge, Andrew Ludberg, and R. W. Hart, students in the College of Engineering. The observations on runs 319 to 500 inclusive were made by the writers, those from 501 to 608 inclusive were made by Messrs. Bingham and Hallauer, who included these data in a thesis submitted for a degree.

The experiments were not made on actual wells, but the apparatus was designed to reproduce as nearly as possible the practical working conditions of the air lift pump.

HISTORICAL NOTES ON THE DEVELOPMENT OF THE AIR LIFT PUMP

The application of compressed air as a means of pumping liquids was first used by Carl Emanuel Löscher, a German Mining Engineer, who in 1797 made some laboratory experiments, and described his invention in a pamphlet entitled "Aerostatisches Kunstgezeug." It was not until half a century later that the idea was put to a practical application, and then in a completely independent manner, by an American named Cockford, who in 1846 succeeded in pumping petroleum from some wells in Pennsylvania.

On May 23, 1865, a United States patent (No. 47,793) was issued to A. Brear on an "oil ejector," which the description and illustration accompanying the patent show to have been an air lift pump of the annular tube type (see page 34).

The idea was again revived by Mr. J. P. Frizell who obtained a patent on an air lift pump, dated Oct. 19, 1880. His invention was apparently made independently and without knowledge of the work done in this field by others, and grew out of his invention of a method of compressing air on which he was granted a patent on January 29th, 1878 (No. 199,819).

The Frizell method of compressing air consists in introducing the air within a column of water descending through a vertical shaft or pipe, from whence the mixture flows through a horizontal tunnel at the top of which the air is collected by means of a suitable receiver and from which it may be conducted to any desired point by a pipe. The water divested of the air passes through the tunnel and rises to the surface through an ascending shaft at the other end. The invention was based on the knowledge that air drawn into a current of water, descending through a vertical shaft or pipe with a

velocity greater than that with which air bubbles would rise in still water, will be carried down with the descending column, and will be subjected to a pressure corresponding to the depth attained. The amount of air which may be carried down and compressed by a current of water depends upon the quantity of water and the difference of head available between inlet and outlet of the tunnel. Although the bubbles of air are actually moving downward their velocity relative to that of the water is upward. They, therefore, have a retarding effect on the velocity of the water due to fluid friction between the air and the water. The larger the quantity of air introduced the smaller will be the size of the water passages between the bubbles, which, with constant head, will result in a slower velocity of the water, until the limit is reached when the downward velocity of the water is just equal to the relative upward velocity of the air. From observation of these facts it was apparent that if compressed air be introduced at or near the submerged bottom of a vertical pipe in sufficient quantity, it will, in rising through the water in the pipe, cause the water to acquire an upward velocity. Mr. Frizell in the specifications of his air lift patent (No. 233,499) expressly states that his method of pumping is a reversal of the principle of his method of compressing air, and since in the latter device the air was admitted in the form of small bubbles, so in the pump also it was admitted through a great number of small orifices with the object of producing small bubbles, so as to aerate the water, as illustrated in Fig. 4.

The air lift pump was used to increase the discharge of flowing wells as early as 1884, a patent (309,214) being issued Dec. 16th of that year to S. S. Fertig on an annular tube type of pump.

Apparently without any knowledge of the previous inventions Werner Siemens in 1885 made use of the air lift pump for draining a mining shaft near Berlin. In France, Laurent in 1885 and Goudry in 1886 used a similar contrivance, which they called an "emulseur," for pumping sulphuric acid.

The term air lift, as applied to the above described method of pumping, was first used by Dr. Julius G. Pohle in the specifications for his patent (No. 487,639) which was issued Dec. 6,

1892. The chief distinction between this type of pump and that of Mr. Frizell lies in the method of introducing the air. To use his own words, "The invention * * * consists in improved processes and apparatus whereby the compressed air is delivered in bulk into the lower end of the water eduction pipe, and the water and air are caused to ascend through said pipe in distinct alternate layers of definite dimensions." In the specifications of his patent he explains his understanding of the working of the pump as follows:

"I have discovered that when air of suitable pressure is allowed to enter in a constant stream and in suitable quantity into an eduction pipe at or near its lower end when it is submerged in water while its upper end rises above the water about the same distance that its lower end is submerged, the compressed air thus introduced will at first expel the standing water from the pipe in an unbroken column free from air, and subsequently, by the continued inflowing of the compressed air under a pressure just sufficient to overcome the resistance of the water outside of the eduction pipe, it will arrange itself in alternate layers with the water, while the latter flows into the lower end of the eduction pipe by force of gravity until it is discharged at the upper or exit end of the pipe. This alternate interposition of determinate quantities of air between the also determinate quantities of water elongates the entire column of air and water, thus facilitating, without materially adding to the weight of the column, the discharge of the water at a higher level than would be the case were these air sections or layers absent. I have also discovered that under the above mentioned conditions the compressed air will not escape through the water overlying it, and also that the water overlying the compressed air will not fall back through the underlying air while both are in upward motion, but find that the elasticity stored in the compressed air layer, pressing alike in all directions, forms a temporary water-tight air piston, which lifts the water above it to its final discharge without appreciable loss by leakage or so called "slip," while this compressed air piston after having expended its elastic energy in work of lifting water is dispelled with only a practically unimportant loss

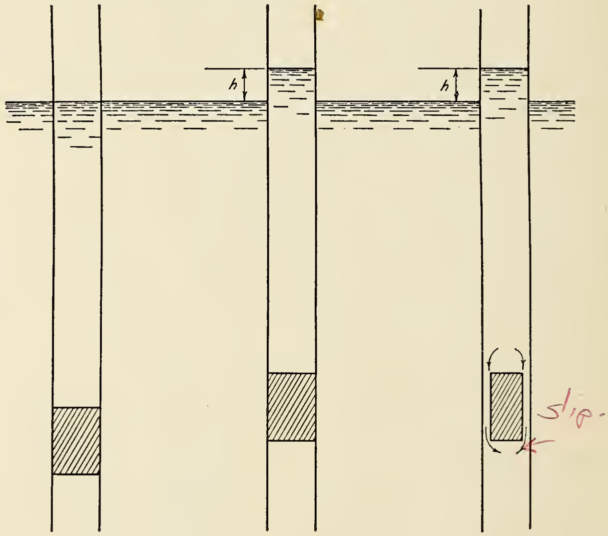
of power.'' In Fig. 3(b) a pump is shown in which the air is in large bubbles or pistons.

In addition to the patents mentioned, many others have been granted covering various supposed or real improvements. Some of these will be mentioned on following pages in the discussion of the features of the pump to which they relate.

THE PRINCIPLE OF THE AIR LIFT PUMP

The precise action going on in an air lift pump is not thoroughly known and it doubtless differs under the various conditions of operation, but the basic principle on which the pump works is simple and may be illustrated in the following manner.

First, consider a vertical pipe, open at both ends and partly immersed in a liquid, as shown in Fig. 1 (a). The liquid will



(a) (b) (c)

Fig. 1.

stand at the same height inside and outside of the pipe. Assume that a block of material, like cork or wood, lighter than

the liquid, made to fit the pipe snugly but able to move without friction, is made to replace part of the liquid near the bottom of the pipe. The hydrostatic pressure on the underside of the block is now greater than the combined weight of the block and the liquid above it. The block and the liquid in the pipe will therefore be pushed up in the pipe, as shown in Fig. 1 (b), until the head h balances the difference between the weight of the block and the weight of an equal volume of the liquid. If more blocks of the light solid material be introduced into the pipe, the liquid will be raised a distance h for each block until the top of the pipe is reached, when an overflow of liquid and blocks will occur leaving an unbalanced head in the pipe, which would keep up the discharge as long as the supply of liquid and blocks was kept up at the bottom of the pipe. In the Pohle air lift system the claim is made that the pump works as described above, with the exception that compressed air is used instead of a light solid, and that work is done by the expansion of the air as it is relieved of the weight of the liquid when approaching the top of the pipe.

A closer approximation is made to usual working conditions in an air lift pump by the illustration (c) in Fig. 1. In this case the block of light material, cork, wood, or air, does not entirely fill the cross-section of the pipe. By virtue of its buoyancy it will tend to rise in the pipe and the liquid in the pipe will tend to flow down past it. The height h, to which the water rises in the pipe in this case, represents the head necessary to force the liquid down through the restricted passage-way past the block. The same conditions would obtain if the single block nearly filling the pipe were replaced by a large number of small blocks. It would require some head h to overcome the resistance offered to the liquid in its flow between the small blocks or between the blocks and the pipe walls. If a sufficient quantity of the small blocks of air or other light material are inserted, the head h will reach the top of the pipe and will cause a discharge of the liquid. The flow of liquid down past the buoyant material is called the slip of the pump. It is the cause of a serious loss of energy.

A commonly accepted conception of the principle of operation of the air lift pump may be had by considering that the

air bubbles, in rising through the water in the discharge pipe, reduce the specific gravity of the mixture and therefore the weight of the column, causing an unbalanced condition between the column inside and outside of the tube. The excess pressure at the base of the column, due to the external water pressure, therefore, forces the mixture above the supply level and out of the top of the pipe. This excess pressure increases with the depth of submergence of the pipe, and the latter must be regulated to suit the height of delivery.

Theory of the Air Lift

Echol's Theory.—An attempt was made by Professor W. H. Echols, to develop a theory of the air lift pump based upon a mathematical analysis of the problem. The results of his studies were presented before the Philosophical Society of the University of Virginia in 1891, but they were not available to the writers.

Harris's Theory.—A further effort in this direction was made by Professor Elmo G. Harris of the University of Missouri, with the purpose of obtaining a rational formula by which a pump could be designed intelligently, and on which experiment could be based. His discussion of the subject was published in the Journal of the Franklin Institute, Vol. 140, p. 32, July, 1895.

In deriving his formulas for the design of a pump the work done by the air is divided into four parts by Professor Harris, as follows:

(1) The kinetic energy in the liquid discharged at the top of the pipe.

(2) The energy necessary to raise the liquid to the top of the discharge pipe.

(3) The energy lost by the liquid slipping down by the bubbles.

(4) The energy consumed by friction in passing through the pipes.

Theoretical expressions may be found for each of the above quantities. That for the slip is too complicated for use in practice, so an approximate formula based on a number of as-

sumptions is derived. For the fourth term the value of the friction factor is assumed, as is the relation of the loss to the velocity. In-as-much as it is not possible to verify the correctness of the individual terms for the losses by experimental means, since the loss due to slip and that due to friction could not be differentiated under working conditions, and in-as-much as the formulas are complicated and difficult to use, they will not be given in detail, but a brief review of the general principles on which they are based will be presented as a further aid to an understanding of the action of the air lift pump.

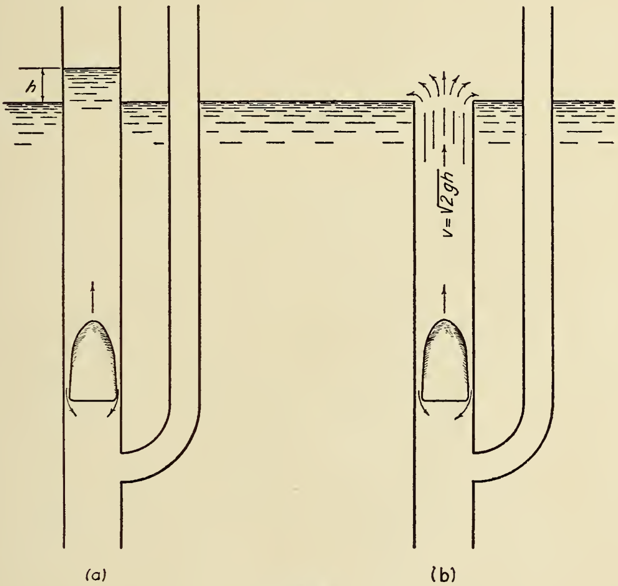


Fig. 2.

In his consideration of the subject Professor Harris first proposes the following problem:

A vertical pipe, open at both ends, is partly immersed in a liquid, as shown in Fig. 2 (a). A quantity of gas is released within the pipe and below the surface of the liquid. What effect will the gas have on the column of liquid and what will be the action of the bubble of gas?

The pipe is assumed to be so large that capillary forces cannot control the action. Then the bubble will ascend in the

pipe. Assuming for the present that no liquid is pumped out of the top of the pipe, then during the ascent the liquid above the bubble must pass by it in order to get below. Hence, the bubble cannot occupy the whole cross-section of the pipe. In order to ascend the bubble must become elongated until the liquid can pass down. In order to pass down through the contraction formed by the bubble, the liquid must have a certain absolute velocity. The presence of this velocity is evidence of the existence of an unbalanced head somewhere above.

Expressions are found for the upward velocity of the air bubbles and for the downward velocity of the water, and from the relations of these quantities the area of cross-section of the bubble and the rate of loss of liquid from above to below one bubble is computed, thereby giving a basis for finding the loss of energy due to slip.

Under the conditions of the above problem all of the useful energy supplied by the air is wasted in fluid friction caused by the water slipping past the bubble.

A closer approximation to working conditions is illustrated in Fig. 2 (b), in which the arrangement is the same as in the preceding problem with the exception that the top of the pipe is flush with the surface of the supply reservoir. In the first problem the bubble produced the standing head h. In the absence of the standing head in this problem, the liquid will flow out of the top of the pipe with a velocity theoretically equal to $\sqrt{2gh}$. Under the conditions of this problem the entire column of liquid in the pipe will be moving upward. The downward velocity of the water past the bubble will not be actual but only relative to the velocity of the bubble, but the loss due to slip is assumed to be the same as under the conditions of the first problem.

In air lift pumps as actually operated the bubbles are not always of the proper size to fill the pipe in the manner assumed above. In the pump specified in the Frizell patent, for example, the air is admitted to the water, as already described, in the form of very minute bubbles. When the size of the bubble is small the surface tension in the liquid tends to compress the bubble into a sphere. When the bubbles are small their motion

is irregular and the formulas deduced by Professor Harris for loss due to slip are not supposed to hold.

In his book on *Compressed Air*, published in 1910, Professor Harris has modified his original theory, and shows that the slip varies as the square root of the volume of the bubble, and that the head produced is independent of the size of the bubbles, hence it would seem desirable to have the air in the form of small bubbles.

Anderson's Theory.—A simple theory of the air lift pump, proposed by Mr. Robert M. Anderson, was published in Bulletin No. 53 of the Hudson Engineering Company in 1905. In developing this theory static conditions were assumed to exist in the pump. Under such conditions the pressure at the air inlet due to the depth of submergence is equal to that produced by the mixture of air and water in the eduction pipe. The lift is found by computing the length of eduction pipe required to give a pressure equal to that due to the submergence. This length is inversely proportional to the average density of the mixture. To find the latter quantity an expression is developed for giving the mean volume of the air, while expanding isothermally from its volume at the inlet to its volume at atmospheric pressure. The various terms when combined give the volume of air at barometric pressure required to pump one volume of water, as

$$q_b = \frac{h_l}{h_s \dfrac{p_b}{p_i - p_b} \log_e \dfrac{p_i}{p_b}} \tag{1}$$

in which

q_b = discharge of free air at the pressure p_b.

h_l = the lift, in feet.

h_s = the depth of submergence, in feet.

p_b = barometric pressure.

p_i = pressure at the air inlet in the foot-piece.

For convenience of reference these and all other symbols used in this bulletin have been tabulated and defined on page 9.

Under the static conditions assumed for developing this theory, there would be no losses of head, such as those occasioned by entrance to the eduction pipe, pipe friction, slip, elbow loss, etc.,

and accordingly no terms for these quantities are found in the formula. To adapt the formula for practical use a constant, found by comparing with experimental results, has been introduced giving

$$q_b = 1.9 \frac{h_1}{h_s \dfrac{p_b}{p_i - p_b} \log_e \dfrac{p_i}{p_b}} \tag{2}$$

It is not claimed that this formula gives accurate results, but only approximations.

Gibson's Theory.—This theory, published in 1908 by A. H. Gibson in his "Hydraulics and Its Application," is based on the same fundamental ideas as the preceding one except that it is not confined to static conditions. Under operating conditions the column of mixed air and water in the eduction pipe is not long enough to create a pressure at the air inlet sufficient to balance that due to submergence, the difference being made up in the losses of pressure due to friction, etc. Mr. Gibson takes account of the losses due to friction and velocity at exit, introducing terms for the loss of head due to these causes so that formula (1) becomes

$$q_b = \frac{h_1 + h_p + \dfrac{v_b^2}{2g}}{h_s \dfrac{p_b}{p_i - p_b} \log_e \dfrac{p_i}{p_b}} \tag{3}$$

Lorenz's Theory.—A very simple mathematical theory, explaining the action of the air lift pump, was published by Dr. H. Lorenz, in Zeitschrift des Vereines Deutcher Ingenieure, Vol. 53, page 545, April, 1909. The formulas he deduces take account of the losses of energy occasioned by slip, pipe friction, etc., and are therefore of practical use in designing air lift pumps, provided the necessary experimental coefficients are known. The theoretical discussion in Dr. Lorenz's article is therefore given in full below. Let

p_i = the pressure in the foot-piece.

p_b = the barometric pressure acting on the surface of the water in the well and also on the discharge end of the pipe A, Fig. 3.

u_w = the density of the fluid pumped.
w_w = the weight per second of the water pumped.
w_a = the weight per second of the air discharged through the pipe B.
u_i = the density of the air at the air inlet in the foot-piece.

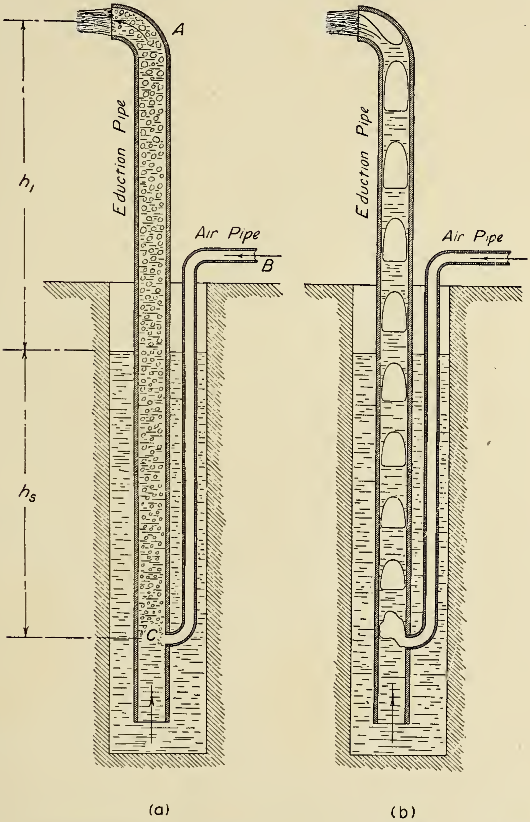


Fig. 3.—Comparison of the Frizell and Pohle Systems of Operation.

u_b = the density of the air at the discharge end of pipe A.
v_i = the velocity of the liquid in the pipe A below the air inlet.
c_e = the coefficient of entrance.
h_s = the depth of submergence.

Referring to Fig. 3 (a), it may be seen that during the operation of the pump the following equation of heads holds between

the point C in the pump and a point at the same elevation outside the pump:

$$h_s - \frac{p_i - p_b}{u_w} = \frac{v_i^2}{2g}\left(1 + c_e\right) \tag{4}$$

For flow in the discharge pipe A the following differential equation holds on account of the variable value of the density u of the mixture of gas and liquid:

$$dh - \frac{dp}{u} = \frac{vdv}{g} - cv^2\,dh \tag{5}$$

in which v equals the variable velocity, and p the pressure at any point; and with the variable specific weight of air as u_v, equation

$$\frac{w_a + w_w}{u} = \frac{w_a}{u_v} + \frac{w_w}{u_w} \tag{6}$$

designates the momentary volume of the mixture $w_a + w_w$.

If the mixture of air and fluid is very intimately commingled; that is, if the air penetrates the fluid in the form of small bubbles, it can be assumed that the air expands isothermally, so that

$$u_v = \frac{p}{p_b}\,u_b \tag{7}$$

By means of equations (6) and (7) the fundamental formula (5) becomes

$$dh - \frac{w_a}{w_a + w_w}\,\frac{p_b\,dp}{u_b\,p} - \frac{w_w}{w_a + w_w}\,\frac{dp}{u_w} = \frac{vdv}{g} - c\,v^2\,dh \tag{8}$$

Integrating this equation between the limits $h_s + h_l$ and 0, p_i and p_b, and v_i and v_b (the velocity of the mixture at the discharge end of the eduction pipe) there results

$$-\left(h_l + h_s\right) + \frac{w_a}{w_a + w_w}\,\frac{p_b}{u_b}\,\log_e\frac{p_i}{p_b} + \frac{w_w}{w_a + w_w}\,\frac{\left[p_i - p_b\right]}{u_w} =$$

$$\frac{v_b^2 - v^2}{2g} + \int_0^{h_l + h_s} c\,v^2\,dh$$

Replacing the last term in this equation, for the sake of simplicity, by assuming a mean coefficient c_p so that

$$\int_0^{h_1 + h_s} c\ v^2\, d\, h = c_p \frac{1}{d} \frac{v_b^2}{2g} \tag{9}$$

there results

$$-\left(h_1 + h_s\right) + \frac{1}{w_a + w_w}\left(w_a \frac{p_b}{u_b} \log_e \frac{p_i}{p_b} + \frac{w_w}{u_w}\left(p_i - p_b\right)\right) =$$

$$\frac{v_b^2 - v_i^2}{2g} + c_p \frac{1}{d} \frac{v_b^2}{2g} \tag{10}$$

Adding this equation to (4) gives

$$\frac{w_a}{w_a + w_w}\left(\frac{p_b}{u_b} \log_e \frac{p_i}{p_b} - \frac{p_i - p_b}{u_w}\right) =$$

$$h_1 + \frac{v_b^2}{2g}\left(1 + c_p \frac{1}{d}\right) + \frac{v_i^2}{2g} c_e \tag{11}$$

Neglecting the second term on the left hand side of the equation, which will be very small in comparison with the first term on account of the large difference between the values of u_w and u_b, w_a and w_w, and neglecting w_a in the denominator, this equation reduces to the simple form

$$\frac{w_a}{w_w} \frac{p_b}{u_b} \log_e \frac{p_i}{p_b} = h_1 + \frac{v_b^2}{2g}\left(1 + c_p \frac{1}{d}\right) + \frac{v_i^2}{2g} c_e \tag{12}$$

In developing this energy equation Dr. Lorenz assumed the velocity of air entering the foot-piece as equal to that of the water; that is free from any losses due to impact which may be readily assumed on account of the small kinetic energy of the air.

Now let

$$l_i = w_a \frac{p_b}{u_b} \log_e \frac{p_i}{p_b} \tag{13}$$

the work of isothermal expansion of the weight of air w_a, and

$l_o = w_w h_l$ the work done in lifting the fluid weight w_w, from which the hydraulic efficiency

$$e = \frac{l_o}{l_i} = \frac{w_w h_l u_b}{w_a p_b \log_e \frac{p_i}{p_b}} \tag{14}$$

can be computed with the aid of equation (12)

$$\frac{1}{e} = 1 + \frac{v_b^2\left(1 + c_p \frac{l}{d}\right) + v_i^2 c_e}{2 g h_l} \tag{15}$$

For the practical use of these formulas it will be better to eliminate the velocities v_b and v_i, by introducing the volumes q_b and q_w of weights w_a and w_w and using the area of the discharge pipe a_p, by means of the following formulas:

$$\begin{aligned} w_a &= q_b u_b & \qquad w_w &= q_w u_w \\ q_b + q_w &= a_p v_b & \qquad q_w &= a_p v_i \end{aligned} \tag{16}$$

Writing now in place of equation (12)

$$\frac{q_b}{q_w} \frac{p_b}{u_w} \log_e \frac{p_i}{p_b} = h_l + \left(\frac{\left(1 + c_p \frac{l}{d}\right)\left(q_b + q_w\right)^2 + c_e q_w^2}{2 g a_p^2}\right) \tag{17}$$

and differentiating this equation with respect to q_b, putting

$$\frac{d q_w}{d q_b} = 0,$$

there results as a requirement for maximum discharge q_w:

$$\frac{1}{q_w} \frac{p_b}{u_w} \log_e \frac{p_i}{p_b} = \frac{1 + c_p \frac{l}{d}}{g a_p^2} \left(q_b + q_w\right) \tag{18}$$

or in connection with equation (17), that is after eliminating the pressures p_i and p_b,

$$\left(1 + c_p \frac{l}{d}\right)\left(q_b^2 - q_w^2\right) = 2 g h_l a_p^2 + c_e q_w^2 \tag{19}$$

If now the maximum discharge determined from the capacity of the well, and the area a_p of the discharge pipe determined from the diameter of the well, and also the lift and the known coefficients c_e and c_p are given, the volume of free air required may be computed by means of the formulas (18) and (19) from

which the submergence h_s can then be computed by means of equation (4). For these fixed conditions equation (17) then gives the relations between any desired values of q_b and q_w using the same pressure p_i.

There may be other losses of energy than those accounted for by Dr. Lorenz, such as the loss due to the elbow or bend which generally forms the upper end of the pump. In comparing the experimental results of the Wisconsin experiments with Dr. Lorenz's theory (see page 77), his formulas have been modified to take account of the elbow loss, and in computing experimental values of the coefficient of pipe friction and slip, a term has been introduced to correct for the loss of energy due to friction in the air pipe (see page 73).

Green's Theory.—In the Engineering and Mining Journal of Aug. 7, 1909 (Vol. 88, p. 251), Leonard M. Green has published an article entitled "Efficiency of the Air Lift as a Solution Pump," in which he discusses mathematically the theory of the air lift, amount of air required, minimum air pressure, efficiency of the lift under given conditions, etc.

He makes the assumption that the water and air rising in the eduction pipe are in layers; the layers of water being equal in volume and the layers of air being of equal weight. Formulas are deduced for computing the ratio of the volumes of water and free air in each layer for given conditions of lift and submergence and for giving the number of these layers, or the volumes of water and air discharged.

No provision is made in the formulas for correcting for entrance loss or for the loss caused by the elbow, at the top of the eduction pipe, which may amount to as much as 15 per cent. of the total work done. Nor has any account been taken of the slip. An attempt has been made to correct for pipe friction by assuming that the velocity in the tail-piece of the eduction pipe is equal to the velocity of flow of water in a clean iron pipe of length equal to that of the eduction pipe and under a difference of head equal to that caused by the compressed air. The experiments made by the writers indicate that this last assumption may be approximately true for some ratios of volume of air to volume of water, but that it is very far from the truth when this ratio is small.

By neglecting the entrance and elbow losses and making the above assumption as to pipe friction the author computes theoretical efficiencies of more than 90 per cent. for small amounts of air, and draws the conclusion that under proper working conditions the total combined efficiency of the compressor and lift should not be less than 70 per cent. Experiments do not justify this opinion.

The Green formulas are not so convenient for use as the Lorenz formulas, so no attempt has been made by the writers to supply the missing terms or to work out experimental coefficients for use with them.

METHOD OF OPERATION

To start the operation of an air lift pump requires a greater air pressure than is necessary for normal operating conditions. When the air supply is first turned on, the air pressure must be greater than that due to the submergence of the air inlet, while after the discharge of the liquid from the pump has commenced the pressure at the air inlet will be reduced by the amount of the entrance and velocity heads of the liquid entering the eduction pipe. The conditions existing while starting an air lift pump are accurately illustrated and described above in connection with Fig. 2 (a) with the exception that instead of only one bubble of air there would be many. When a sufficient number of bubbles have been introduced to raise the head through the entire lift, some of the liquid will begin to spill out over the top of the pipe. The loss of this liquid causes a reduction in the pressure in the eduction pipe, which under some conditions allows a sudden influx of the high pressure air, resulting in a violent discharge of liquid and air which may exhaust the store of compressed air. Following this the liquid would regain its full static head, requiring the operation to be started over again.

To prevent such intermittent action the escape of air into the eduction pipe must be controlled. It should be throttled the instant the discharge of liquid commences. That intermittent action does not always occur is probably due to the effect of friction in the air pipe. As this friction increases with the square of the velocity, it is evident that in long pipes of small cross-section it will serve to some extent as a governor, tending to control the discharge of air.

DESCRIPTION OF AN AIR LIFT PUMPING PLANT

The Pump

The essential structural features of the air lift pump are exceptionally simple and few in number, and this fact constitutes one of its principal advantages. In its simplest form, as illustrated in Fig. 3, it consists of a pipe for the discharge of the water and a smaller pipe for conveying compressed air to it at a point near its lower end.

The Eduction Pipe.—The discharge pipe is designated by various writers as the eduction pipe, lift tube, lift pipe, and rising main. It should not touch the bottom of the well or reservoir from which it is to pump but should be elevated above it so as to freely admit the water or other liquid through its lower open end. This end of the pipe should, however, be submerged below the liquid surface a distance which, our experiments indicate, should be greater than the height above the water surface to which the liquid is to be lifted. This latter distance is technically called the lift of the pump. The distance measured from the water surface down to the point of admission of the air into the eduction pipe is known as the submergence of the pump. Submergence is generally expressed as a percentage of the total length of the pump, measured from the point of air inlet to the point of discharge. The discharge should be free into a reservoir at atmospheric pressure. Submergence and lift should be measured from the elevation of the water as it stands under working conditions rather than under static conditions.

The Foot-Piece.—In most air lift pumps the compressed air from the air pipe enters the eduction pipe through a casting designed to cause the air to enter in a special manner. The casting used for such a purpose is technically called a foot-piece.

The type of foot-piece devised by Mr. Frizell is shown in Fig. 4. In the specifications for his patent it is described as follows:

"Into the bottom of the rising-pipe is fitted the hour-glass-shaped pipe 5, inclosing between the two pipes the annular space E E.

"The upper end of the pipe 5 is perforated with a great number of minute orifices, F, as indicated by the black dots.

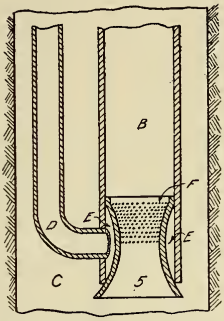


Fig. 4.—Frizell's Foot-Piece.

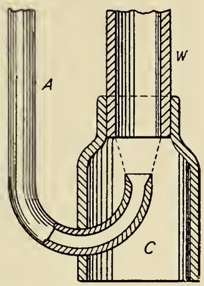


Fig. 5.—Pohle's Foot-Piece.

The lower end expands to a greater width than that of the rising-pipe in order to diminish the resistance of the water in entering.

"The pipe D, leading from the source of compressed air opens into the annular space E E.

"The pipe D, which conveys the compressed air may pass down in the pit C, as shown, or inside the rising-pipe B, or outside the pit C in the ground, if preferred."

Dr. Pohle's foot-piece is illustrated in Fig. 5. The description of it, taken from the specifications for his patent, is as follows:

"The exit end of the air pipe is enlarged by beveling off the inner edge thereof, in order to permit the free delivery of the air in mass or bulk, and thus to avoid the formation of air bubbles. The enlargement C of the pipe W is of sufficient area to compensate for the space occupied by the exit end of the air pipe A, and said end of said pipe A passes through the vertical side of the enlargement C, as shown, and derives support therefrom."

Quite a large number of different foot-pieces have been devised and patented and in most cases extravagant claims have been made for them as regards their effect in increasing the

efficiency of the pump. A few of the types will be illustrated and discussed on a following page, in connection with the description of the experiments carried on at the Hydraulic Laboratory of the University of Wisconsin.

As will be shown later, experiments indicate that changes in the form of the foot-piece have little if any effect on the efficiency and capacity of the pump, other than the effect due to the amount of obstruction of the water passages; a factor which differs in the various types.

Tail-Piece.—Most forms of foot-piece are arranged for the attachment of a pipe onto their lower ends, thus extending the eduction pipe some distance below the point of air admission, for the purpose of preventing the escape of compressed air from the bottom of the eduction pipe. The pipe used for such an extension is termed a tail-piece. The tail-piece is often made a larger size of pipe than is the remainder of the eduction pipe. The length and size to be used for a tail-piece are problematical.

A number of distinct types of air lift pump have been produced through the various methods that have been devised for piping the wells. The methods in most frequent use are illustrated in Figs. 6 and 7 and are described below.

Side Inlet Pump.—The side inlet pump, in which the air pipe is on the outside of the discharge pipe, is shown at (a) in Fig. 6. The air pipe is connected to the bottom of the eduction pipe by means of standard fittings, special castings, or one of the various patented foot-pieces, examples of which are illustrated in Figs. 11 and 12. This method is used when the well is large enough to admit of the air and water pipes being placed side by side from top to bottom and is probably the most economical of the systems shown.

Annular Air Tube Pump.—Fig. 6 (b) shows the annular air tube pump in which the well top is sealed and the air passes down through the annular space between the discharge pipe and the air pipe or well casing.

In the illustration accompanying the 1865 patent of A. Brear's annular tube pump, a foot-piece is shown attached to the lower ends of the eduction and air pipes. This nozzle is so

arranged that the air is directed upward into the center of the eduction pipe, the liquid entering the lower part of the foot-piece and surrounding the air nozzle. The air is introduced differently in the Bacon pump, which has been quite extensively

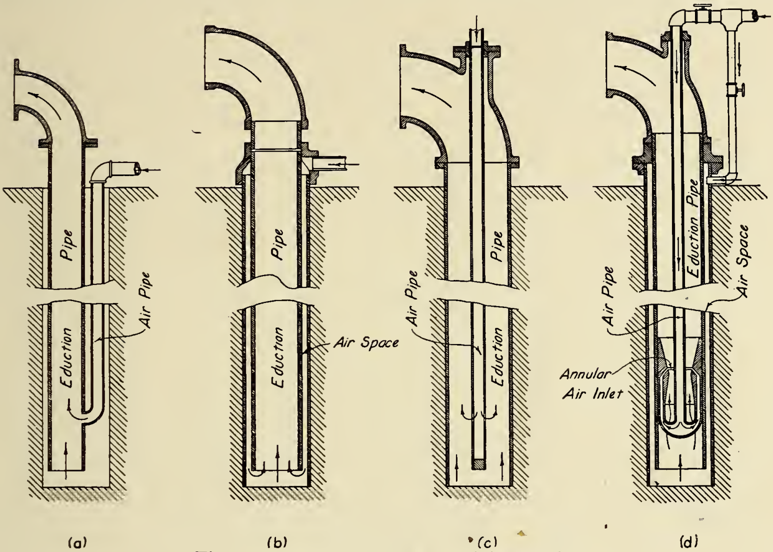


Fig. 6.—Different Methods of Piping Wells.

used. In the original patent (No. 542,620) of James E. Bacon, issued July 16, 1895, the statement is made that it was found "advantageous to make an opening into the uptake-pipe near the bottom end thereof, so that the air may flow through that opening in a uniform or nearly uniform stream." Many annular tube pumps have been built with no foot-piece or opening in the side of the pipe. In such pumps the air forces the water level in the well down until the bottom of the discharge pipe is uncovered. Air then enters the discharge pipe and the pressure in the annular space is lowered. This causes the fluid to rise again in the air space and discharge pipe until the pressures balance and then the operation is repeated. This causes the water in the well approaching the bottom of the eduction pipe to surge more violently than it would if it were allowed to rise in the well around the eduction pipe to its normal height, as it does in the side inlet system. It is claimed for

pumps built in this way that this surging promotes the entrance of the water and air into the eduction pipe in a manner conducive of high efficiency.

Central Air Tube Pump.—Fig. 6 (c) shows the central air tube pump which uses the well casing as the discharge pipe, and introduces the air through a small pipe usually fitted with some special device or foot-piece attached to the bottom through which the air escapes. Usually a number of small holes are drilled, or a number of slits cut into the lower joint of pipe and the end plugged. An objection to this method is that when the well is cased for only a portion of the distance, the air and water may escape out of the well into fissures in the rock. The hydraulic radius of the water passage in the discharge pipe is reduced by the air pipe, which increases the frictional losses and so diminishes the efficiency, but in this method of piping the entire cross-section of the well, less the area of the air pipe, is available for use as a discharge pipe; so a well piped in this way will have a greater theoretical capacity than wells of the same size piped by the other methods; notwithstanding the obstruction caused by the central air pipe. This fact is shown by the following comparison of the three methods. Assuming in each case that the wells are of 6 inches diameter, the largest eduction pipe which can be got into the well with a 1-inch air pipe beside it, is 3½ inches in diameter, while in the annular tube method of piping a 4½-inch eduction pipe can be accommodated. In the central tube system it is assumed that a 1½-inch air pipe is used with the 6-inch casing serving as the eduction pipe. The tabulated values of the areas and perimeters of the pipes were taken from the table of standard dimensions of wrought iron and steel pipe published in the Crane Company's catalogue. It may be noted in the following tabulation that the hydraulic radius of the central air tube pump is less than that of the annular tube pump, but the net area of the former is nearly twice as large as that of the latter. The discharge through a pipe under a given head is proportional to the product of the area and the square root of the hydraulic radius of the pipe. This product has been calculated and tabulated in the last column and shows the relative capacities of the wells piped according to the three different methods, as-

suming the value of the coefficient of pipe friction and slip to be the same in all three cases.

	Nominal Size of Well. in Inches.	Nominal Size of Eduction Pipe, in Inches.	Nominal Size of Air Pipe, in Inches.	Approximate Net Area of Eduction Pipe, in Square Inches.	Approximate Wetted Perimeter, in Inches.	Hydraulic Radius, in Inches.	Discharge Function.
				a_p		r	$a_p \sqrt{r}$
Side Inlet Pump...........	6	3½	1	9.89	11.15	0.89	9.33
Annular Tube Pump...........	6	4½	6	15.96	14.62	1.13	16.9
Central Air Tube Pump...........	6	6	1½	26.05	25.02	1.04	26.5

Combination Pump.—Fig. 6 (d) shows a combination of the annular air tube and central air tube methods of piping. It is evident that the hydrostatic head in the well cannot be greater than that due to the ground water to permit of continuous operation. Therefore, no special advantage is to be gained in introducing compressed air above the water surface in the well, unless the increased surging, due to the less depth of water on the outside of the eduction pipe, might effect the size of bubbles of air admitted. The results of the authors' experiments show, that with the well piped according to the side inlet method using a Harris Air Pump Company's foot-piece, there was no appreciable difference when compressed air was introduced above the water surface in the well and when the well was open to atmospheric pressure, the percentage of submergence and lift being the same in both cases. The cut shows this system with a patented foot-piece on the end of the air-pipe.

Multiple Air Lift Pump.—When the lift is very high and the proper submergence difficult to obtain, the arrangement shown in Fig. 7 may be used where the cross-section of the well permits of its use. This arrangement employs a series of successive lifts and it is claimed that it works more economically than when the water is raised in a single lift. The cross-sec-

tional area of the ordinary deep well will not permit of such an arrangement, but it may be used to advantage in a mine shaft.

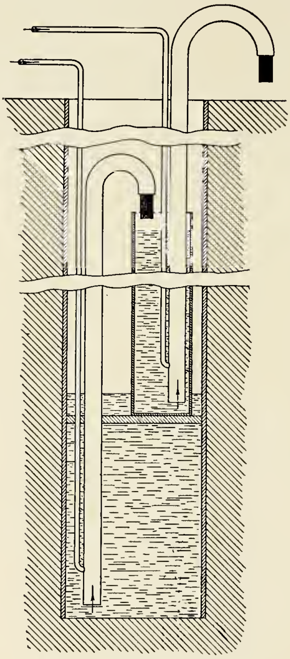


Fig. 7.—Multiple Air Lift.

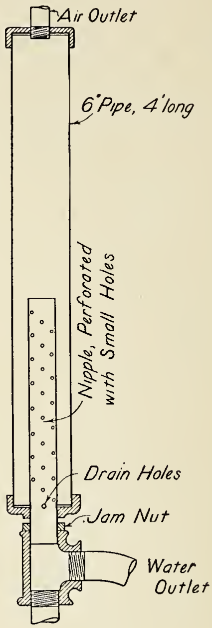


Fig. 8.—Air Separator.

Return Air Pump.—In rising through the eduction pipe there is a transfer of heat between the air and the water; the temperature of the two being practically equal at the point of discharge. Therefore, where the air lift is being used to pump from underground supplies, the temperature of the air issuing from the discharge pipe will be cooler than the atmosphere during the warm months of the year. For each five degrees fall in the temperature of the free air entering the compressor, a saving of about one per cent. in the expenditure of energy used in doing the work of compression may be effected. Hence, where the wells are situated in close proximity to the power house, considerable economy may be effected by connecting the air inlet of the air cylinder of the compressor with the top of the well casing head. An air separator used for this purpose consists of a cylindrical drum about 18 inches in diameter and 8 or 10

feet long, attached to the casing head from the side of which the discharge from the well passes out and from the top the air is piped to the compressor. An air separator is shown in Fig. 8. The return-air method of piping may be used with any of the types of pumps shown in Figs. 6 and 7.

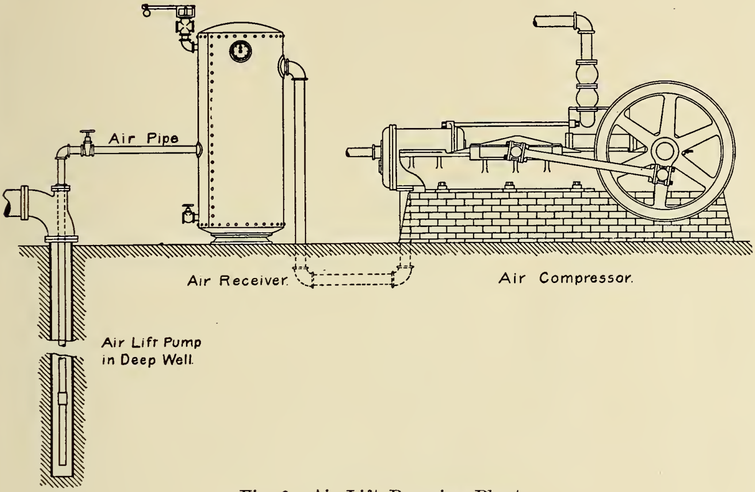


Fig. 9.—Air Lift Pumping Plant.

The air separator described above is useful also where it is desired to pump to points situated some distance from the well, as described on page 42.

Diverging Outlet Pump.—When the eduction pipe is of uniform diameter throughout, as shown in Figs. 3, 6, 7 and 9, the discharge occurs at quite high velocity, resulting in a considerable loss of energy. To conserve this kinetic energy of the water Mr. Jos. Price, an English engineer, fitted his pump with an eduction pipe which increased in diameter towards the top, so that as the compressed air expanded in rising the velocity would not be greatly increased. This device could be used with any type of foot-piece and any method of piping. A few experiments by the authors indicate that a considerable saving may be effected by the use of a diverging outlet of proper design.

The Plant

An air lift pumping plant comprises the motive power, an air compressor, an air receiver, and an air pipe leading to one or more pumps such as have been described in the preceding paragraphs. Fig. 9 serves to illustrate in a general way the machinery and other essential apparatus.

The compressor and receiver should be located where the expense of installing and operating the plant will be the least. They are often situated a considerable distance from the wells. The power used to drive the compressor may be either steam, electric, water, or internal combustion engines.

The Compressor.—The type of compressor installed will depend on the pressure required to pump the wells, the nature and amount of power available for compressing the air, and the number and size of the wells. Where the pressure required is small and the quantity to be compressed not very large, the ordinary straight line or duplex compressor may be used. Where high air pressures are necessary economy demands the cross compound type fitted with an intercooler.

The Receiver.—The receiver is used to store and equalize the air pressure. It acts in much the same way as the air chamber on a force main and reduces the effects of the pulsations of the compressor. It also acts as a separator to catch the water and oil which are carried by the air. It is quite necessary to provide some kind of a separator for this purpose to prevent the air pipes becoming clogged, and where a foot-piece with small air openings is used it is especially desirable to have the air free from any clogging material. The air receiver is usually built of boiler iron and designed so as to permit a steady flow of air to the well. The air from the compressor passes down from the top of the receiver through a pipe and discharges beneath the surface of some water which is usually kept in it. The outlet pipe for the air is located near the top of the receiver, and a drain is provided at the bottom to carry away the oil and water.

The Air Line.—From the receiver the main air line runs to the wells. The piping to the wells should be arranged to avoid

unnecessary valves, elbows and bends, as these reduce the efficiency of the plant. The same precaution should also be taken in the design of the water pipes. A valve should be placed on the air main in the power house so that the wells may be controlled from a central point. It is desirable to place a regulating and a stop valve at each well so that after the proper amount of air has been adjusted to the conditions of lift, submergence, etc., at the well, it will not be necessary to disturb the adjustment in order to shut down the well.

In the following pages the discussion will be confined to the air lift pump alone, leaving out of consideration the efficiency of the air transmission pipes, compressors and other appurtenances, which have an important bearing on the desirability of installing air lift pumping plants, but the consideration of which is beyond the scope planned for this bulletin.

DISADVANTAGES OF THE AIR LIFT PUMP

The air lift pump, in common with every other device, has a number of disadvantages, the principal ones being its low efficiency, the great depth of submergence required and its poor adaptability to conditions requiring the discharge to be conveyed great horizontal distances.

Low Efficiency.—The most serious of the above mentioned disadvantages is the low hydraulic efficiency of the pump. The pump is generally credited with efficiencies of only 25 to 33 per cent, but notwithstanding the low efficiency of the pump itself, the entire air lift pumping plant in some cases develops a duty which compares favorably with other systems of pumping.

Great Depth of Submergence.—A single air lift pump cannot be used in a shallow well or reservoir except to raise the liquid a very small distance, owing to the high percentage of the total length of the pump which must be submerged to give good efficiencies. This fact limits the field of the air lift pump principally to deep well pumping. The multiple stage pump described on page 37 overcomes the difficulty, but probably at the cost of reduced efficiency.

Limited Horizontal Pumping.—Several plants have been installed where the air lift was used to pump the water a considerable horizontal distance after it had been raised to the surface of the ground, but such plants are not considered efficient. The air in passing through the horizontal or even an inclined pipe, is not likely to be evenly distributed throughout the cross-section of the pipe, but is likely to pass along under the upper side, allowing a large space in the lower portion of the pipe for the water to slip back past the bubble. In a horizontal pipe the air cannot exert any buoyant effort to aid in discharging the water, and its expansive force, which might be used in overcoming pipe friction is not likely to be effective on account of the serious amount of slip which occurs under these conditions. Where it is desired to convey the water to a point distant horizontally from the well, the eduction pipe

should be carried vertically above the well a height equal to the friction head of the water in the horizontal conductor, and at its top it should be fitted with an air separator, such as the one described on page 39. From the separator the water would flow by gravity to the desired point.

Aeration.—The thorough aeration of the water pumped is generally regarded as an advantage, but under some circumstances it is a disadvantage. It doubtless promotes the rusting and consequent destruction of the eduction pipe and in some cases causes a deposit of salts which clogs the water passages, especially in the foot-piece. The opinion has also been expressed that compressed air causes an excessive growth of algae. The bacterial content of water is somewhat increased by the air lift unless the air supply is filtered.

ADVANTAGES OF THE AIR LIFT PUMP

The air lift pump possesses many features which give it decided advantages over other types of pumps, when applied to certain conditions.

Large Capacity.—Its principal claim to superiority lies in its large capacity. When the conditions are suitable for its installation, an air lift pump will discharge more liquid from a well of small bore than will any other type of pump. This is due to the fact that almost the entire cross-sectional area of the well is available for the flow of liquid and the action is nearly continuous. The quantity that can be discharged by an air lift pump is only limited by the capacity of the well and the expense of pumping at unreasonably high rates; while deep well pumps, the majority of which are single acting, limit the discharge by the allowable piston speed, which usually does not exceed 100 feet per minute. The air lift affords a ready means for testing the capacity of a well even if it is not to be permanently installed.

Low Maintenance Cost.—Owing to the simplicity of the pump the expense of maintenance of the plant is very low, and is due principally to the expenses in connection with the compressor. The operation of the air lift is exceedingly simple and the life of the pump is almost indefinite. Sometimes the air pipes and foot-piece become clogged with the oil carried over from the compressor cylinders and in that case have to be removed and cleaned, but this rarely occurs, and when it does the cost is small compared with the cost of replacing a mechanical pump. The fact that there are absolutely no moving parts in the well makes the pump especially fitted for handling dirty or gritty water, sewage, mine water and acid or alkaline solutions in chemical or metallurgical works, or other corrosive liquids. Mechanical pumps suffer from fine sand in the water, which cuts the packing, plungers, and valves in a short time and makes frequent repairs necessary. To repair such pumps they have to be stopped for a period of several days, resulting in a consequent waste of time and increase in expenses. Liquids

that attack metals such as brine, sulphuric acid, etc. may be pumped by the air lift pump, because the pump and appurtenances may be replaced at a small expense and loss of time. The application of the air lift as a dredge pump has been tried and found successful, but it has not been extensively used for this purpose.

Low Operating Cost.—In places where the wells are scattered over a considerable area, or are remote from the power house, the air lift pump has an advantage over the steam driven pump. In a deep well pump driven by steam each well must be equipped with a separate engine and working barrel, which entails heavy condensation losses through long steam supply pipes. The expense of attendance of a plant of this sort with its scattered pumping units is great. In the air lift pump the transmission loss is much smaller and as no attendance at the well is required, they may be put in operation or controlled by a valve in the power house.

Not Affected by High Temperatures.—Fluids of different densities and temperatures may be handled to advantage by the air lift in cases where the use of other types of pumps would be prohibited. In the case of a hot liquid the air absorbs part of the heat of the liquid and hence is increased in volume, so that the discharge of liquid for the same expenditure of free air is greater with hot than with cold liquids. This results in a considerable gain in efficiency for the pump.

Aeration.—Where the water is to be used for a domestic supply and there are impurities in it such as iron, it has been noticed that the iron is oxidized by the aeration of the water and the supply is thereby improved. Aeration is especially advantageous in the pumping of sewage on account of the aid it gives in the oxidation of the impurities.

Reliability.—Air lift pumps are not liable to sudden stoppages or breakdowns.

WISCONSIN EXPERIMENTS

The experiments made by the writers at the Hydraulic Laboratory of the University of Wisconsin, were begun during the summer of 1908 and were continued at various times thereafter with modifications in the apparatus.

Notation

The notation and definitions used in the following discussion are given below:

"Reading" is the term used to designate a single value obtained by the inspection of the scale of an instrument.

"Run" is used to designate such a combination of readings, made under practically constant conditions, as form a complete unit in the result.

"Series" is used to designate those runs made with varying rates of pumping but with constant conditions of apparatus.

DESCRIPTION OF APPARATUS—1908 EXPERIMENTS

The 1908 experiments, comprising runs 1 to 318, inclusive, were made with the apparatus arranged as shown diagrammatically in Fig. 10.

Eduction Pipe.—In this series of experiments the eduction pipe, which consisted largely of 1¼-inch glass tubing supported by a slotted 2-inch iron pipe, was exposed to view, thus affording opportunity to observe the air and water rising in the pipe. The upper end of the glass pipe was coupled to a 1¼-inch iron pipe, about a foot long, on the upper end of which was a cast iron elbow fitted with a nipple 2 inches long. A piece of canvas fastened to this nipple deflected the spray downward into a 4-inch galvanized spout. This arrangement provided a free discharge into the air at the elevation of the elbow.

Foot-Piece.—The foot-piece used in the 1908 experiments was a No. 2 Harris air pump* having a 1¼-inch discharge, a 1½-inch suction, and ½-inch air pipe. A sectional view of the foot-piece used is shown in Fig. 11 (a) and an exterior view in Fig. 12.

The Harris pump, as described in patent No. 814, 601, consists essentially of an ejector having a contracted passageway formed by a sleeve snugly fitted into its upper end, and having immediately below the sleeve a nozzle screwed into an air pipe. The walls of the ejector are enlarged about the air tube so that the dimensions of the passageway through the ejector are substantially uniform. The air nozzle in the ejector differs from the form described in the above patent, in having the air discharge into the body of the ejector through a circular slot in the end of the nozzle, instead of from an open diverging tube. The sleeve and nozzle are shown in their relative positions in Fig. 12.

Tail-Piece.—As used in the 1908 experiments the foot-piece was connected by a short nipple to a reducing flange on the top of a 6-inch flanged cast iron tee. This arrangement made

* Made by the Harris Air Pump Co., Indianapolis, Ind.

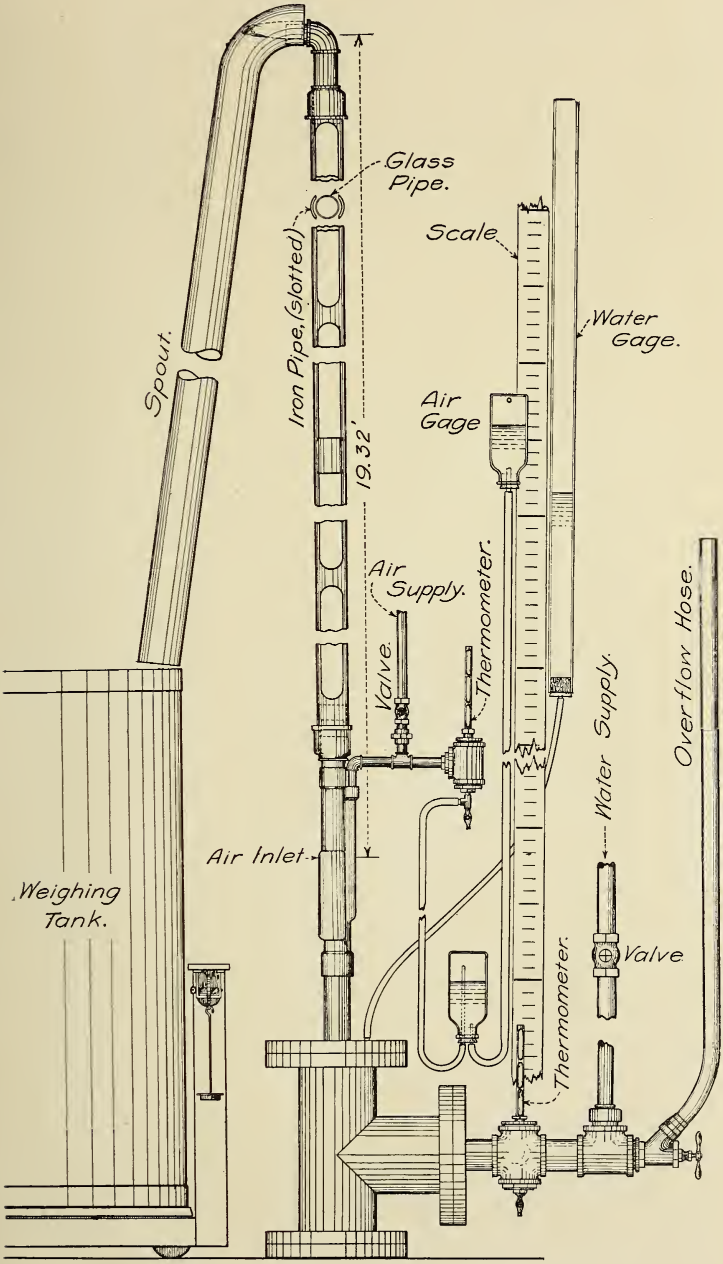


Fig. 10.—Experimental Apparatus—1908 Experiments.

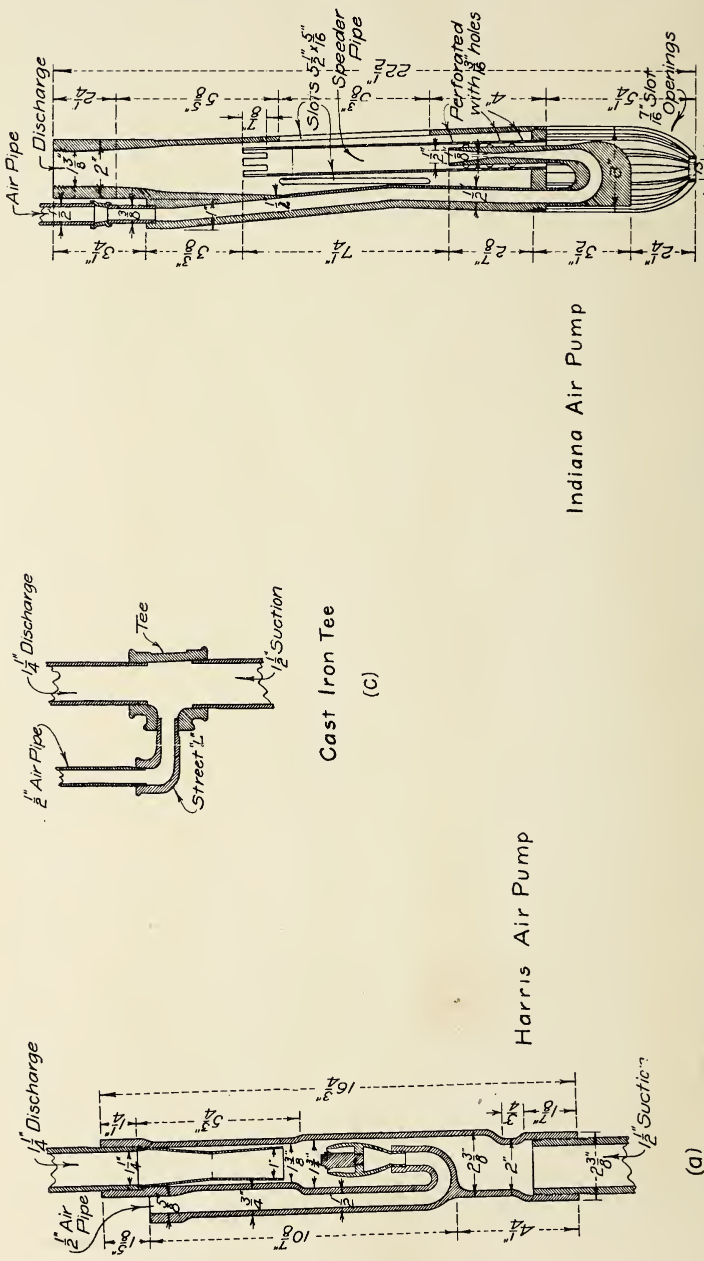


Fig. 11.—Foot-Pieces Used in Wisconsin Experiments.

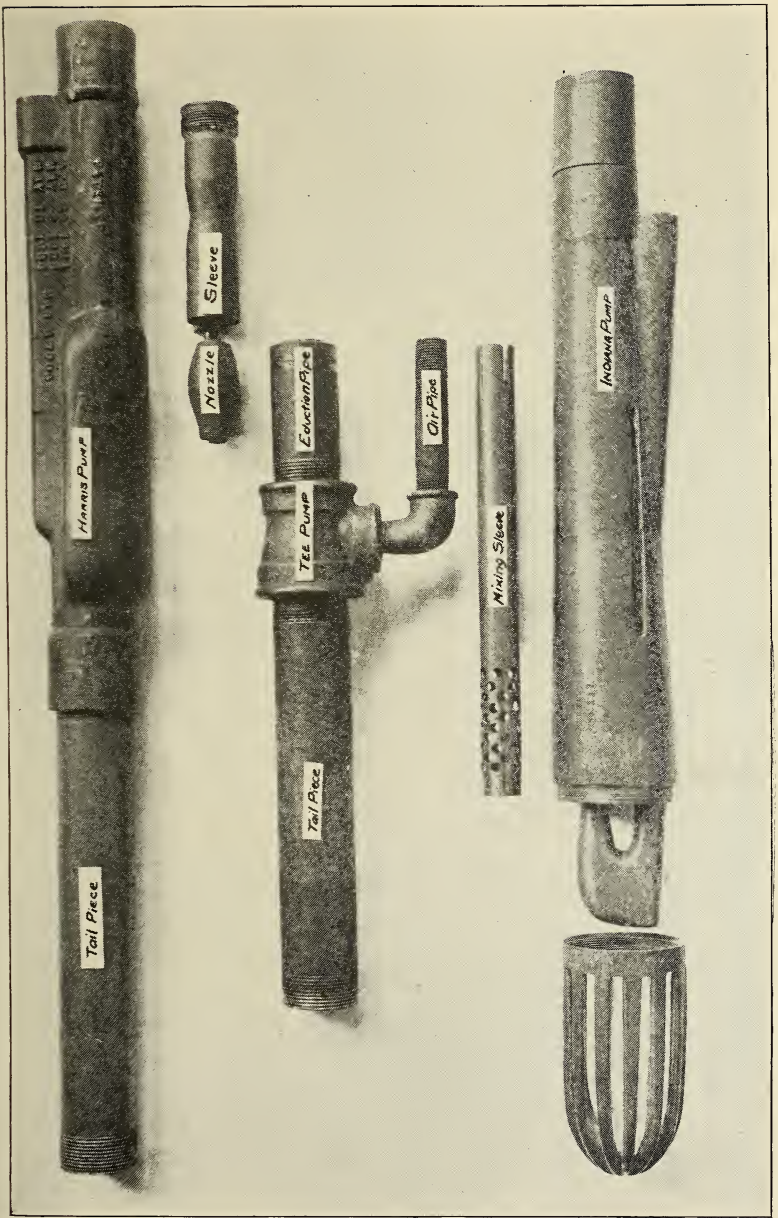


Fig. 12.—Foot-Pieces Used in Wisconsin Experiments.

the entrance to the pump approximately one foot below the air inlet.

Water Supply.—The water supply, controlled by a 1-inch valve, entered the tee through the branch, the water passing through a 2-inch cross in which was inserted an iron thermometer well. The bulb of the thermometer in the well was surrounded by mercury in order to make the thermometer respond quickly to changes in the temperature of the water.

For the purpose of determining the head of water at the air inlet, a ¼-inch nipple was tapped into the top of the 6-inch tee and was connected by means of a 1¼-inch glass tube, marked water gage in Fig. 10. A large glass tube was used in order to reduce the amplitude of the oscillations due to the variations of pressure caused by the surges of air in the eduction pipe. The head of water was varied during the experiments by adjusting the height of the outlet of the overflow hose. This overflow hose was quite necessary for the proper working of the pump as it served as a reservoir and standpipe, which regulated the flow of water to the well and kept the submergence constant at different rates of pumping. The rate of pumping was determined by weighing, on a platform scale, the water discharged in a given interval of time.

Air Supply.—The air used in the experiments was drawn from one of the storage tanks of the University pneumatic pressure water works plant. This tank had a capacity of approximately 3,000 cubic feet and was normally maintained at about 140 pounds pressure, but during the air lift experiments the pressure was often reduced, owing to the use of the air, to the minimum under which the air lift would work. An automatic reducing regulating valve controlled the flow from the storage tank so as to maintain a practically uniform pressure in the receiving tank at the air orifice described below.

The quantity of air supplied to the air lift was controlled by a valve in the ½-inch supply pipe near the foot-piece. The temperature of the air was measured by a mercury thermometer placed in a well similar to the one used to measure the temperature of the water. It was placed in a 2-inch tee on a branch leading from the main air pipe. A rubber tube, one end of which connected to the tee and the other end of which

terminated in a glass tube, served to transmit the air pressure at the tee to the air space in the upper part of the lower bottle on a water gage. The pressure head in the air at the 2-inch tee was indicated in feet of water by the difference of elevation between the water surfaces in the two bottles. A 3/8-inch hole in the side of the upper bottle insured the pressure in this bottle being equal to that of the atmosphere. The two bottles were connected by rubber hose, the ends of which terminated in short glass tubes under the surface of the water in both bottles. As the pressure of the air used in the

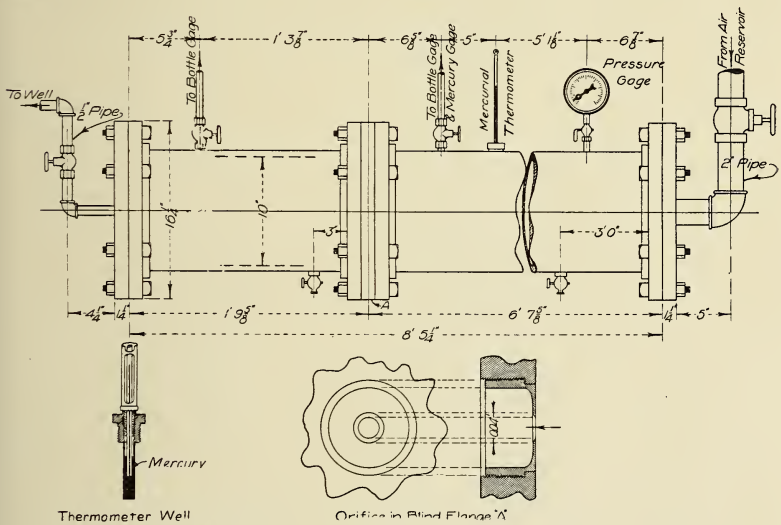


Fig. 13.—Drum and Orifice for Air Measurement.

different experiments varied, the height of one or both of the bottles was changed so as to prevent the surface of the water disappearing in the tube or overflowing through the vent hole. Bottles were used instead of glass tubes in this gage, in order to provide larger water surfaces, thus reducing the oscillations of the surfaces to one or two hundredths of a foot, instead of two feet or more which occurred when a tube was tried.

Air Measurement.—To determine the quantity of air used in the experiments a standard sharp edged orifice, shown in Fig. 13, was used. Its diameter was measured by a Starrett micrometer caliper reading to 1/1000 of an inch and was found

to be 0.480 inches. It was made of brass and was arranged to screw into an iron plate flush with its surface on the high pressure side. The iron orifice plate was bolted between two sections of 10-inch iron pipe. The air supply entered the longer section of 10-inch pipe through a 2-inch pipe. A Bourdon pressure gage connected to the drum was used to indicate the pressure in the drum while adjusting the pressure regulating valve. During the experiments the pressure in the high pressure side of the drum was more precisely determined by means of a mercury U tube gage, shown at A in Fig. 15, connected to the drum by a ¼-inch iron pipe at a point 6 inches from the face of the orifice plate. During the 1908 experiments about 100 feet of ½-inch pipe connected the orifice drum with the air lift pump. In Fig. 13, one of the thermometer wells, used for measuring the temperature of the air and of the water at the pump, is shown in detail. A mercurial thermometer placed in a similar well was used to determine the temperature of the air in the orifice drum.

To measure the difference of head on the two sides of the orifice a bottle gage of special design, was connected to the orifice drum by ¼-inch pipe at the points shown in Fig. 13. The bottle gage is shown in Figs. 14 and 15. It consisted of two inverted clear glass bottles about half filled with water and connected by a glass U tube, which passed through the stoppers but ended below the water surface. The air pressures on the two sides of the orifice were transmitted to the air spaces in the bottles by tubes which passed through the stoppers and ended above the water surface. When the pressures were equal the water stood at the same level in both bottles, but when unequal the difference of pressure was balanced by the difference in the heights of the water surfaces. This difference in height was measured by means of two pointed brass rods which were coated with grease and slid through holes in the rubber stoppers. In use the two rods were raised or lowered by a small worm gear until their points were in the level water surfaces in the bottles, the relative elevations of the points being then determined by means of the scales and verniers attached to the rods and reading to 1/1000 of a foot. To get the actual difference of elevation of the points,

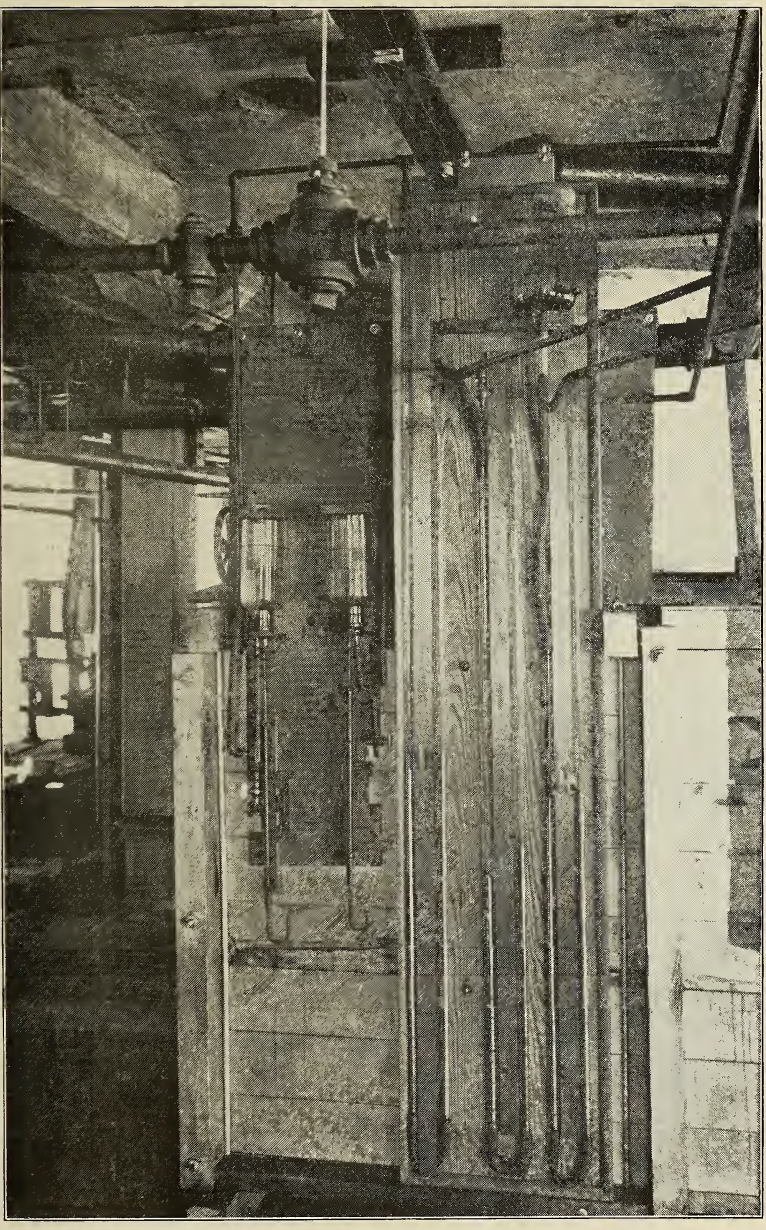


Fig. 14.—Gages Used in 1909 Experiments.

or of the water surfaces, it was necessary to deduct from the difference indicated by the vernier readings a similiar difference indicated when the air pressure in the bottles was equal, as when the tubes were open to the atmosphere. The scale and vernier on the high pressure bottle were arranged to give readings increasing downward, while those on the low pressure bottle gave readings increasing upward. This arrangement made the computations easy, for in order to calculate the true difference of elevation of the water surfaces it was only necessary to subtract the sum of the initial or equal pressure vernier readings from the sum of the average vernier readings of any run. This arrangement of the verniers and scales also nullified the effect of any leakage of water during an experiment, since a lowering of the water surfaces by leakage would increase the high pressure readings the same amount that it would decrease the low pressure readings, the sum of the two remaining the same. The leakage through the stoppers was very slight; not requiring replenishing in a year and a half.

DESCRIPTION OF APPARATUS—1909 EXPERIMENTS

The 1909 experiments, comprising runs 319 to 608, inclusive, were made with the purpose of determining the effect of variations in the length of the eduction pipe, the form of the foot-piece, the presence of compressed air in the casing, and other features. These experiments required that the apparatus as originally set up be changed somewhat.

The general arrangement of the apparatus as used in the 1909 experiments is shown in Fig. 15.

Well.—There was some doubt as to whether the arrangement, used in the 1908 experiments, for introducing the water into the eduction pipe represented closely enough the working conditions of a pump in an actual well, and it was further desired to find the effect of compressed air outside of the eduction pipe. In the 1909 experiments the pump was, therefore, placed in a well which consisted of a 6-inch wrought-iron pipe 22 feet long, capped at the top and flanged at the bottom to a 6-inch tee.

Eduction Pipe.—The eduction pipe was the same as used in the 1908 experiments. The entire glass portion of the pipe with its supporting slotted 2-inch iron pipe was suspended in the well from the cap. During runs 319 to 379, inclusive, the length of the eduction pipe from the air inlet to the center of the elbow was 19.32 feet as in the previous experiments. During runs 381 to 440, inclusive, the length was 26.74 feet, the increase being made by adding a length of 1¼ inch iron pipe above the well top. During runs 441 to 460 the length was 41.50 feet, the addition being made as above. Runs 461 to 500 inclusive were made with different forms of foot-pieces which made slight variations in the length, 42.08 feet for runs 461–480 and 41.6 feet for runs 481–500.

Foot-Piece.—During runs 319 to 460, inclusive, the same Harris foot-piece was used as was used in the 1908 experiments. An Indiana foot-piece* was used during runs 461 to 480. It was a 1½-inch foot-piece reduced to 1¼-inch by a reducer at

* Presented by the Indiana Air Pump Co., Indianapolis, Ind.

the top. During runs 481 to 500 the foot-piece used consisted of a common cast-iron reducing tee, the eduction pipe, tail-piece and air pipe entering the tee only so far as allowed by the standard threads on their ends, as shown in Fig. 11 (c). The Harris foot-piece has already been described on page 48. The Indiana foot-piece was developed from the Harris foot-piece, the object, as stated in the patent specifications, being to produce a simple, efficient, center-nozzle air lift. This foot-piece is shown in Figs. 11 (b) and 12, the various parts being indicated. In Fig. 12 the strainer has been removed to show the lower part of the nozzle, and the mixing tube or sleeve, into which the nozzle discharges the air, has also been removed and placed beside the foot-piece. The reducer can be seen at the upper end of the foot-piece.

Tail-Piece.—In the 1908 experiments the tail-piece was only about 2 inches long. Under the conditions of the apparatus used in these experiments, any air which may have escaped from the bottom of the eduction pipe into the 6-inch tee would have been carried into it again by the water. Under the conditions of the apparatus used in the 1909 experiments such would not have been the case. A tail-piece consisting of 1 foot of 1½-inch pipe was, therefore, screwed into the lower end of the Harris foot-piece, the length suitable for the conditions of our experiments having been determined by correspondence with the pump makers. The same piece of pipe was used as a tail-piece in connection with the tee used as a foot-piece in runs 481 to 608. No tail-piece was used on the Indiana foot-piece.

Water Supply.—Water was introduced into the well by means of a 2-inch pipe connecting the branch of the 6-inch tee with the University main. The depth of the water in the well was regulated by means of a 1½-inch overflow pipe connected at the lower end to the supply pipe and discharging at its upper end into the air. By varying the length of the overflow pipe any desired depth of submergence could be obtained. Provision was made, as in the 1908 experiments, for taking the temperature of the water as it entered the well, by screwing a thermometer well into a 2-inch tee in line with the supply pipe. The water was discharged at the upper end of the eduction pipe

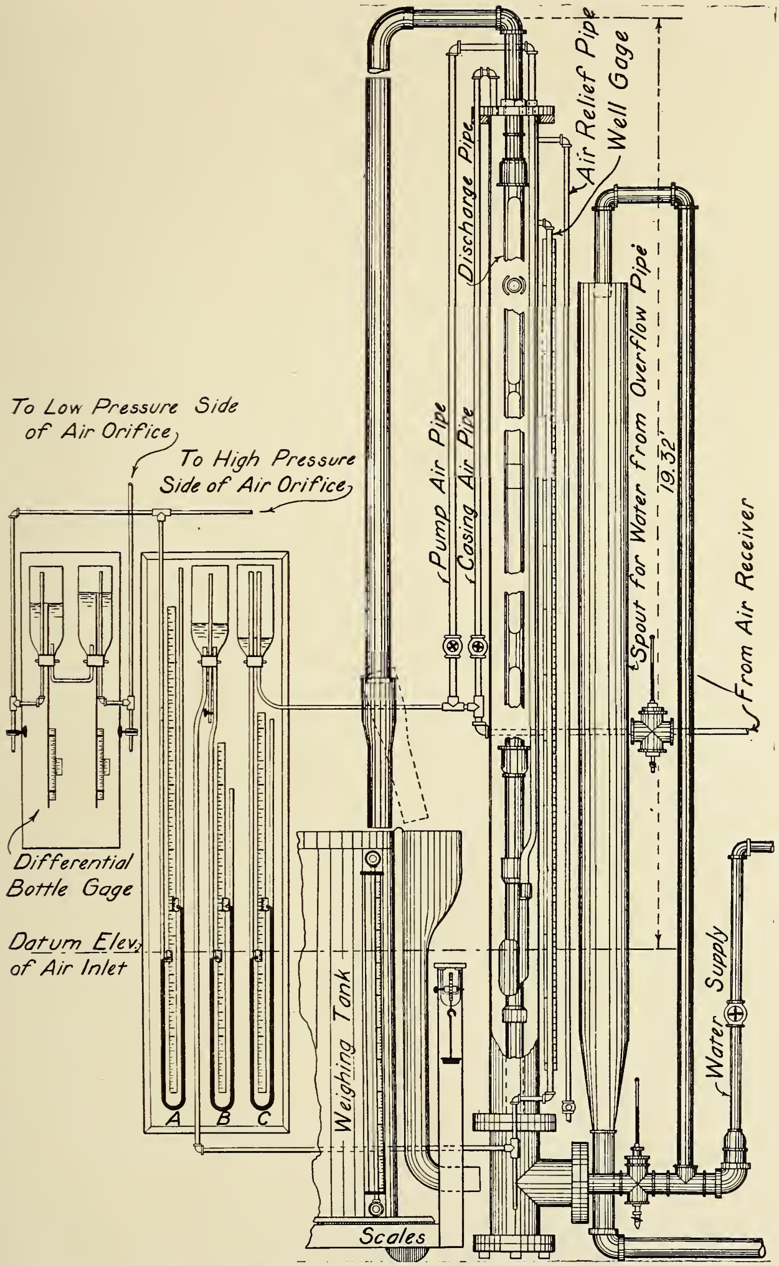


Fig. 15.—Experimental Apparatus—1909 Experiments.

at atmospheric pressure into a conductor pipe, by means of which it was led to the weighing tank or discharged as waste.

Air Supply.—The source of air and the apparatus for controlling it and for measuring it were the same as in the 1908 experiments, but in the 1909 experiments the pump was set up only a few feet distant from the air measuring orifice. The air line was, therefore, shorter in these experiments. At the well the air line divided into two branches; one branch, marked pump air pipe in Fig. 15, supplying the pump through a ½-inch pipe, which entered the well through a stuffing box in the cap of the well, the other branch, marked casing air pipe, introducing the air into the casing above the water in the well, through a ½-inch pipe screwed into the cap of the well.

Gages.—There were four gages used in making these experiments. The differential bottle, described in connection with the 1908 experiments, was used to determine the difference of head on the air orifice. The gage, marked A in Fig. 15, was a mercury U tube used for determining the head on the high pressure side of the orifice. Gage B measured the pressure at the bottom of the well, by means of which the equivalent submergence could be calculated, when air pressure was exerted on top of the water in the well. The actual depth of water in the well was obtained by means of a glass gage attached to the outside of the well, from which the submergence could be directly calculated when the water in the well was open to atmospheric pressure. Mercury gage C measured the air pressure as it entered the pump, the valve in the pump air line being wide open. Air chambers were used on gages B and C to dampen the fluctuations of the gage readings, but this device was unnecessary as the readings were steady except when the water was so low in the well that air entered the pump through the tail-piece. The scales on the gages were made of steel, graduated to hundredths of a foot, and, by means of sliding verniers, readings could be obtained to 1/1000 of a foot.

Leakage Tests.—All pipe joints and other places where an escape of air was possible were tested by applying soap solution, which indicated small leaks by the formation of bubbles. The entire apparatus was made air-tight before any runs were made.

METHODS OF OBSERVING

Owing to the fact that different types of gages were used in the 1909 experiments than those used in the 1908 experiments for making some of the measurements, the arrangement of the data differed somewhat in the latter runs from the arrangement first used. The conditions of operation usually remained quite constant during a run, so that the gage and thermometer readings varied only slightly, if at all. Usually four or five readings of each instrument were made during a run, the length of a run varying from 3 to 15 minutes, and the discharge of water varying from 200 to 1,000 pounds. Time was measured by a calibrated stop-watch; temperatures were measured by mercurial thermometers graduated to the centigrade scale and reading to tenths of a degree, and lengths were measured in feet.

1908 Experiments.—Copies of the complete observed data of runs 30 and 132 are given below as samples to show the con-

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Experiment on Harris Air Lift Pump Run No. 30
Data by McBride, Springer, Miller, + Dodge Computed by Miller + Springer
Date of Experiment July 1, 1908 checked by - E. B. Nelson
General Data Barometer = 29.01 ins. Mercury
Length of Pump = 19.32 ft. Size of Pump = $1\frac{1}{4}$ in.
Zeros of Bottle Gage 0.229 + 0.403 = 0.632

Lift Minus 3 ft.	Duration of Run	Water: Weight in Pounds: Initial	Water: Weight in Pounds: Final	Temp °C	Air: Temp at Pump °C	Air: Water Gage for Pressure at Pump: Lower	Air: Water Gage for Pressure at Pump: Upper	Air: Merc. Gage for Pressure at Orifice: Left	Air: Merc. Gage for Pressure at Orifice: Right	Air: Bottle Gage for Diff Head on Orifice: Left	Air: Bottle Gage for Diff Head on Orifice: Right	Air: Temp. at Orifice °C		
8.36	$10^m 6^s$	0	400	21.6	23.3	15.32	7.03	2.885	5.860	0.270	0.442	24.8		
8.36				21.8	23.3	15.32	7.03	2.885	5.855	0.270	0.442	24.8		
8.36				21.6	23.4	15.32	7.03	2.890	5.850	0.270	0.442	24.8		
8.36				21.6	23.4	15.32	7.04	2.895	5.848	0.269	0.442	24.8		
8.36				21.6	23.3	15.32	7.04							
8.36	606^s		400	21.6	23.3	15.32	7.03	2.888	5.853	0.2698	0.4420	24.8		
3.00						7.03			2.888		0.2698			
11.36						8.29			2.965		0.7118			
											0.6320			
											0.0798			

stancy of the conditions of operation and the method of making the observations. The scale by which data were obtained for

computing the lift and submergence was inverted and placed with its zero three feet below the center of the outlet of the pump. The readings of the scale, from its zero down to the water surface in the water gage (see Fig. 10), were, therefore, three feet less than the true lift.

1909 Experiments.—The apparatus for the 1909 experiments was so arranged that only two men were needed for conveniently making the observations; one man reading the gages while the other took the time of the run, read the thermometers, observed the depth of water in the well, and weighed the water. The gages were read as nearly simultaneously as possible, by first setting the verniers on all the different gages and afterwards taking the readings. About four accurate settings of the gages could be obtained in a ten minute run. The thermometers were read to a tenth of a degree centigrade and the temperature was obtained at least twice during a run; usually at the beginning

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Experiment on Harris Air Lift Pump Run No. 132

Data by McBride, Springer, Miller + Dodge Computed by Miller + Springer

Date of Experiment July 30, 1908 checked by - E. B. Nelson

General Data Barometer = 29.04 ins. Mercury

Length of Pump = 19.32 Size of Pump = $1\frac{1}{4}$ in.

Zeros of Bottle Gage = 0.299 + 0.331 = 0.630

Lift Minus 3 ft.	Duration of Run	Water: Weight in Pounds, Initial	Water: Weight in Pounds, Final	Water: Temp °C	Air: Temp at Pump °C	Air: Water Gage for Pressure at Pump, Lower	Air: Water Gage for Pressure at Pump, Upper	Air: Merc. Gage for Pressure at Orifice, Left	Air: Merc. Gage for Pressure at Orifice, Right	Air: Bottle Gage for Diff Head on Orifice, Left	Air: Bottle Gage for Diff Head on Orifice, Right	Air: Temp. at Orifice °C
0.87	$3^m 21^s$	40	440	26.4	25.8	15.42	0.44	3.140	5.592	0.398	0.428	29.0
0.87				26.4	25.8	15.42	0.44	3.148	5.587	0.397	0.427	29.0
0.86				26.4	25.8	15.42	0.45	3.150	5.583	0.397	0.427	29.0
0.86				26.4	25.8	15.42	0.45	3.154	5.580	0.396	0.426	29.0
0.86				26.4	25.9	15.42	0.45					
0.864	201^s		400	26.4	25.8	15.42	0.45	3.148	5.585	0.397	0.427	29.0
3.000						0.45			3.148		0.397	
3.864						14.97			2.437		0.824	
											0.630	
											0.194	

and end. The method of weighing the water was as follows: The empty tank weighed about 150 pounds, so a 200-pound weight was placed on the scale beam and the water diverted into the tank. When enough water had run into the tank to cause the scale beam to rise, a stop watch reading to $\frac{1}{5}$ of a second

was started. Additional 100-pound weights were then placed on the scale beam and the watch was stopped when the beam rose again. The time and number of weights added while the watch was running were then recorded. The length of a run varied from 3 to 15 minutes depending on the depth of submergence and the amount of air supplied to the pump.

The readings for some of the runs were taken by a single observer, and it was not possible for one man to get more than two sets of gage readings during a run, the length of which was limited by the capacity of the measuring tank. It was entirely unnecessary to take more readings, because as a rule the readings were identical, and two readings of each instrument served as a check to prevent blunders in observing and recording. The complete data of runs 338 and 482 are given below.

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Experiment on Harris Air Lift Pump Run No. 338

Data by Weidner & Stocker Computed by Weidner

Date of Experiment Aug. 13, 1909 checked by - E. B. Nelson

General Data Datum Reading on Submergence Gage = 3.00 ft.

Length of Pump = 19.32 ft.

Barometer = 28.95 ins. Mercury Zeros of Bottle Gages

L 0.313 + R 0.319 = 0.632

Air Orifice				Submergence Gage		Air Gage at Pump		Temperature			Depth of Water in Well*	Weight of Water		Duration of Run
Bottle Gage		Mercury Gage						Air at Orifice	Water at Pump	Air at Pump				
Left	Right	Left	Right	Left	Right	Left	Right					Initial	Final	
0.210	0.211	1.216	3.637	1.104	2.416	1.096	2.472	27.3	24.2	25.6	1.62	180	1080	$7^m 27^s$
0.2095	0.210	1.216	3.637	1.104	2.416	1.096	2.472	27.3	24.2	25.6	1.66			
0.209	0.210	1.211	3.640	1.104	2.416	1.096	2.472	27.5	24.2	25.7	1.70			
0.209	0.210	1.211	3.640	1.104	2.416	1.096	2.472				1.76			
0.2094	0.2102	1.213	3.638	1.104	2.416	1.096	2.472	27.3	24.2	25.6	1.68		900	$4^m 47^s$
			1.213		1.104		1.096	273.0	273.0	273.0				
	0.6320		2.425		1.312		1.378	300.3	297.2	298.6				
	0.4196													
	0.2124													

* Compressed: air above water

The observed temperatures of the air and water at the entrance to the pump were not used in the computations and hence are not tabulated in the final results of Table 1.

Most of the computing was done with a Thatcher calculating instrument and all computations have been carefully checked.

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Experiment on 1¼-Inch Tee Air Lift Pump Run No. 4 82

Data by Weidner Computed by Weidner

Date of Experiment Feb. 23, 1910 checked by - Nelson

General Data Length of Pump = 41.6 ft.

Datum Reading on Submergence Gage = 6.67 ft.

Barometer = 29.42 ins. Mercury

Zeros of Bottle Gages 0.299 + 0.334 = 0.633

Air Orifice				Submergence Gage		Air Gage at Pump		Temperature			Depth of Water in Well	Weight of Water		Duration of Run
Bottle Gage		Mercury Gage						Air at Orifice	Water at Pump	Air at Pump				
Left	Right	Left	Right	Left	Right	Left	Right					Initial	Final	
0.241	0.355	0.790	4.145	0.853	2.873	0.910	3.480	18.0	7.7	18.3	5.6	200	1000	$5^m 34^s$
0.241	0.355	0.790	4.145	0.853	2.873	0.910	3.480	17.9	7.6	16.2	5.6			
			4.145		2.873		3.480	17.9	7.6	16.2				
	0.633		0.790		0.853		0.910	273.0	273.0	273.0				
	0.596		3.355		2.020		2.570	290.9	280.6	289.2	5.6		800	$303^s.4$
	0.037													

METHODS OF COMPUTING

Quantity of Air.—The amount of air supplied to the pump was measured, as previously stated, by means of a circular orifice in a thin brass plate. The following formula derived by Mr. S. A. Moss* was used in computing the discharge through the orifice.

$$q_a = 3860\, c_o\, a_o \frac{p_u}{\sqrt{T_u}} \sqrt{\left(\frac{p_d}{p_u}\right)^{1 \cdot 425} - \left(\frac{p_d}{p_u}\right)^{1 \cdot 712}} \qquad (20)$$

in which

q_a = cubic feet of free air discharged per second.

c_o = a coefficient of discharge.

a_o = area of orifice, in square feet.

p_u = absolute pressure of air at upstream side of orifice, in pounds per square inch.

p_d = absolute pressure of air at downstream side of orifice, in pounds per square inch.

T_u = absolute temperature of air, in degrees Fahrenheit, at upstream side of orifice.

The values of the coefficient of discharge were obtained from the curve shown in Fig. 16, in which the abscissas represent the difference in pressure in feet of water between the up and down stream sides of the orifice, and the ordinates represent the values of the coefficient of discharge for an orifice 0.48 inches in diameter. This curve was plotted from data published in an article ''On the Measurement of Air Flowing into the Atmosphere through Circular Orifices in Thin Plates'' by Mr. R. J. Durley.†

Mr. Durley regards these data as being reliable to within less than one per cent. In view of this fact and the accuracy with which the temperature, diameter of orifice, and difference of pressure were measured, the writers believe the probable error

* American Machinist, Volume 28, page 193, 1905.

† Transactions Am. Soc. M. E. Vol. 27, page 193—1906.

should be within one or two per cent, in measuring the quantity of air.

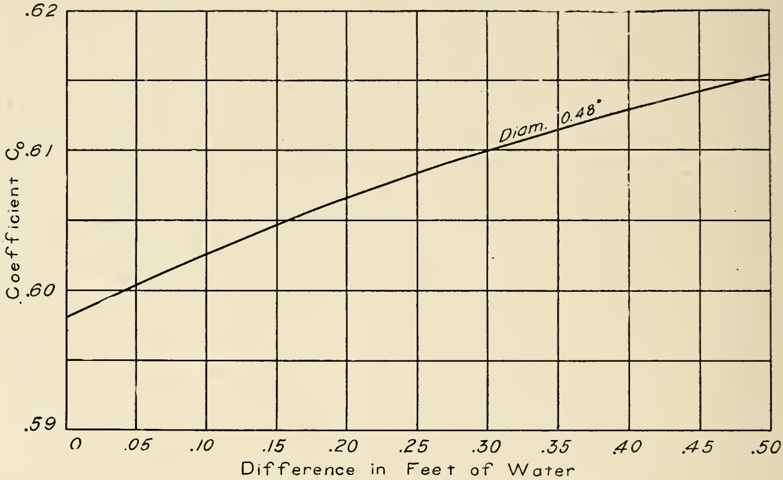

Fig. 16.—Coefficient of Discharge for Air Orifice.

The difference in pressure between the up and down stream sides of the orifice was measured in feet of water by means of the differential bottle gage shown in Figs. 14 and 15. p_u was obtained by the following computation.

(Reading of gage A in feet of mercury $\times$ 5.894)

+(Barometer reading in inches of mercury $\times$ 0.4912)

and p_d by the following

p_u — (Bottle gage reading $\times$ .4333)

The barometer readings were taken from the autographic record charts of the U. S. Weather Bureau. No correction to these readings was made for a standard temperature, as the difference in elevation between the Weather Bureau station and the Hydraulic Laboratory offset this small correction.

T_u being observed in degrees Centigrade a constant was introduced in the formula; the diameter of the orifice being 0.04 of a foot the formula then reduced to the following one

$$q_a = \frac{p_u}{\sqrt{T_u}} \times c_o \times 3.6144 \sqrt{\left(\frac{p_d}{p_u}\right)^{1.425} - \left(\frac{p_d}{p_u}\right)^{1.712}} \qquad (21)$$

The curve shown in Fig. 17 is plotted to give values of the constant times the radical for different values of $\frac{p_d}{p_u}$ which values multiplied by proper values of the coefficient c_o and $\frac{p_u}{\sqrt{T_u}}$ give the discharge in cubic feet of free air per second. As an illustration, the computations for run 338, the data for which are

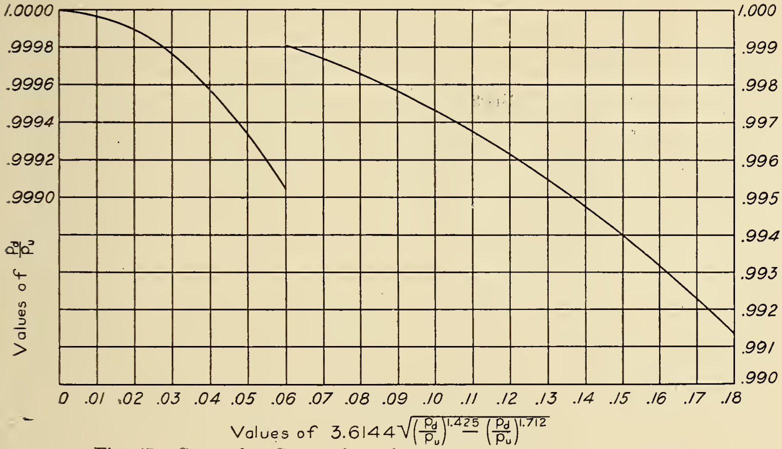

Fig. 17.—Curve for Computing Discharge of Air Through Orifice.

given on page 63, will be used throughout the following discussion.

Average difference in pressure in feet of water = .2124

$p_u = (2.425 \times 5.894) + (28.95 \times .4912) = 28.512$

$p_d = 28.512 - (.2124 \times .4333) = 28.4200$

$T_u = 300.3$

$\sqrt{T_u} = 17.329$

$$\frac{p_u}{\sqrt{T_u}} = 1.6454$$

$$\frac{p_d}{p_u} = 0.9967$$

$$3.6144\sqrt{\left(\frac{p_d}{p_u}\right)^{1.425} - \left(\frac{p_d}{p_u}\right)^{1.712}} = 0.1112 \quad \text{(Curve Fig. 17)}$$

$c_o = 0.6070$ (Curve Fig. 16)
$q_a = 1.6454 \times 0.6070 \times 0.1112 = .11108$

Theoretical Work Done by Air.—Assuming isothermal expansion of the air in its passage through the eduction pipe,—a very reasonable assumption since the air absorbs heat from the water,—the mechanical work L done between the volumes q_2 and q_1, is theoretically as follows*

$$L = \int p dq = p_1 q_1 \int_{q_1}^{q_2} \frac{dq}{q} \; p_1 q_1 \log_e \frac{q_2}{q_1} \tag{22}$$

The work done by one pound of air in expanding from an initial pressure p_1 to atmospheric pressure, (2116.8 pounds per square foot or 14.7 pounds per square inch) at 60° Fahrenheit, the standard temperature of the Moss formula, is:

$$L = p_1 q_1 \log_e \frac{q_2}{q_1}$$

$$p_1 q_1 = p_2 q_2$$

$$q_1 = \frac{p_2 q_2}{p_1}$$

$$\therefore \; L = p_2 q_2 \log_e \frac{p_1}{p_2} \tag{23}$$

The volume of one pound of air at 32° Fahrenheit and 14.7 pounds per square inch pressure is 12.3880 cubic feet.† The volume of one pound of air at 60° Fahrenheit and 14.7 pounds per square inch pressure is, since

$$\frac{p_1 q_1}{T_1} = \frac{p_2 q_2}{T_2}$$

$$\frac{14.7 \times 12.3880}{460 + 32} = \frac{14.7 \times q_2}{460 + 60}$$

$$q_2 = 13.093$$

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* Carpenter's Experimental Engineering 6th Edition, p. 712.
† Trautwine, pages 242 and 320.

The formula for L in foot pounds now becomes

$$L = 14.7 \times 144 \times 13.093 \times \log_e \frac{p_1}{14.7 \times 144}$$

or using logarithms to the base 10,

$$L = 14.7 \times 144 \times 13.093 \times 2.30259 \times \log \frac{p_1}{14.7 \times 144}$$

$$L = 63816.886 \log \frac{p_1}{2116.8} \qquad (24)$$

in which p_1 is expressed in pounds per square foot. The curve Fig. 18 was computed by means of this formula for different values of p_1 and was plotted to read pressures in pounds per square inch. In order to get the total work done, the value of work done in expanding from p_1 to atmospheric pressure is added to the work done in expanding from atmospheric to barometric pressure, both values being obtained from the curve. In the 1908 experiments p_1 was measured by a water gage which gave the pressure in feet of water. In the 1909 experiments a mercury gage was used.

$$p_1 = (1.376 \times 5.894) + (28.95 \times .4912) = 22.330$$

Work done in expanding one pound of air from 22.330 pounds per square inch to 14.7 pounds per square inch = 11600 foot pounds (from curve).

Work done in expanding one pound of air from 14.7 pounds per square inch to 14.22 pounds per square inch = 900 foot pounds (from curve).

Total work = 11600 + 900 = 12500 foot pounds.

Pounds of air used per second = .11108 × .076376 = .008481.

Total work done by .008481 pounds of air in expanding from 22.330 pounds per square inch to 14.22 pounds per square inch = .008481 × 12500 = 106.02 foot pounds per second.

Quantity of Water.—Discharge of water in pounds per second $= \frac{900}{744} = 2.0135.$

Discharge of water in cubic feet per second = 2.0135 × .0160 = .03221.

Discharge of water in U. S. gallons per minute = .03221 × 7.48052 × 60 = 14.4580.

Submergence.—The gage marked water gage in Fig. 10 measured the lift in the 1908 experiments, from which the percentage of submergence was calculated by subtracting the lift from the total length of the pump and dividing the result by the total length. In the 1909 experiments the submergence was measured by the mercury gage B, Fig. 15. For runs 319–440, inclusive, the datum reading on the submergence gage was

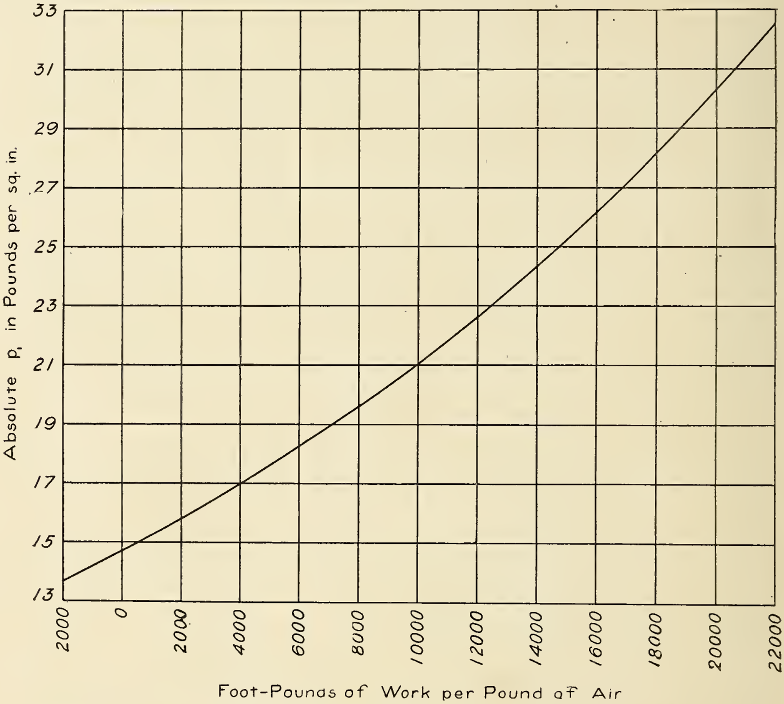

Fig. 18.—Curve for Finding Energy per Pound of Air at Various Pressures.

+ 3.00 feet, while for runs 441–500 it was —6.67 feet. By datum reading on the submergence gage is meant the scale reading at the elevation of the air inlet of the pump. The following formula was used to calculate the percentage of submergence for the runs of the 1909 experiments.

[(Difference in feet of mercury, gage B, × 13.6) + (Left reading of gage B) — 3.00 feet or + 6.67 feet] ÷ Total length of pump in feet.

Percentage of submergence for run 338=

$$\frac{(1.312 \times 13.6) + 1.104 - 3.00}{19.32} = 82.54$$

Lift.—Observed directly in 1908 experiments. In the 1909 experiments computed from following formula:

Lift=Total length of pump — (Percentage of submergence $\times$ total length of pump).

Lift for run 388 = 19.32 — (82.54 $\times$ 19.32) = 3.375 feet.

Actual Work Done in Lifting Water.—The product of the discharge in pounds per second and the actual lift in feet was taken as a measure of the actual work done. A few writers on the air lift pump have added the friction head in the eduction pipe to the actual lift, in computing the work done, but in the opinion of the writers the eduction pipe should be considered as a part of the pump. Actual work done in lifting water for run 338 = 2.0135 $\times$ 3.375 = 6.7950 foot pounds.

Efficiency—The efficiency of the pump was computed on the basis of the ratio of actual work done in lifting the water to the theoretical work inherent in the air, when expanding from the pressure at the gage to barometric pressure. By reference to Figs. 10 and 15 it will be seen that the gage pressure was measured within a few feet of the foot-piece in the 1908 experiments, but that in the 1909 experiments the pressure was measured at a distance of 20 to 30 feet from the foot-piece in line with the air supply pipe. The efficiency, then, as computed is independent of the efficiency of the compressor and conveying air pipes to the well, but includes a short length of air pipe such as would be necessary to conduct the air from the top of the well to the foot-piece. The loss due to friction in the air pipe and air nozzle is discussed on p. 73. Efficiency for run

$$338 = \frac{6.795}{106.026} = 6.409 \text{ per cent.}$$

Ratio of Volume of Air to Volume of Water.—Obtained by dividing quantities in column 2 of Table I by quantities in column 6. Ratio of volume of air to volume of water for run

$$338 = \frac{.1108}{.03221} = 3.449$$

Velocity of Water in a 1¼-Inch Tail-Piece.—Obtained by dividing the discharge of water in cubic feet per second by the cross sectional area in square feet of a 1¼-inch pipe. Velocity for run 338 $= \frac{.0322}{.00825} = 3.779$ feet per second.

EXPERIMENTAL COEFFICIENT

An experimental coefficient for use in connection with the Lorenz formulas has been computed from the data of the Wisconsin experiments. The method used in making this computation is explained in detail below.

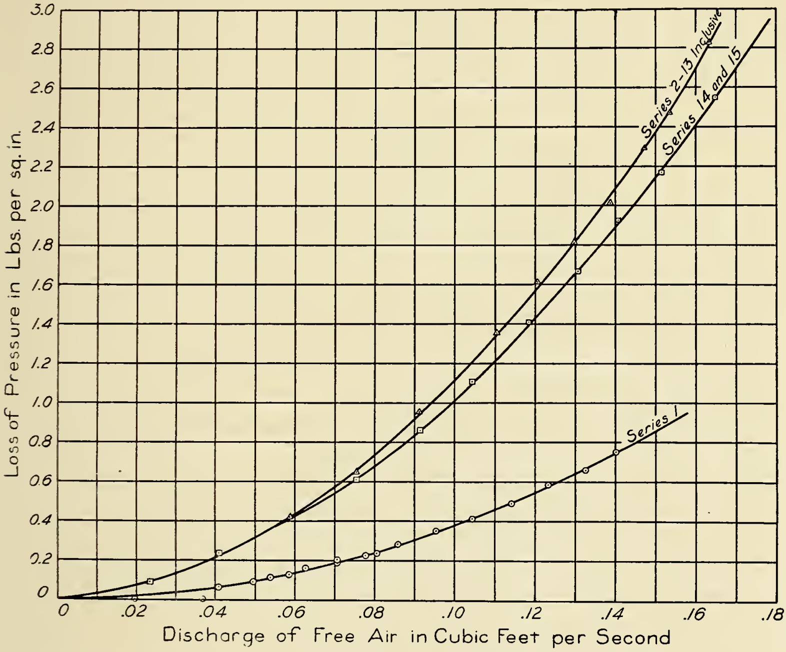

Fig. 19.—Loss Due to Friction in Air Pipe and Air Nozzle.

Loss Due to Friction in Air Pipe and Nozzle.—A considerable loss of energy was caused by the drop in pressure between the point in the air main, where the pressure was measured, and a point in the foot-piece opposite the air inlet. The amount of this drop in pressure was determined by discharging air at various rates through the pump, when all water was drained out of it. The indications of the gage gave the head required to cause the discharge from the air nozzle, and to overcome the

frictional resistances in the air pipe with its elbows and other fittings, when discharging into the atmosphere. The curves in Fig. 19 show this loss of pressure for various discharges for three different lengths of air pipe with the Harris foot-piece. The lower curve, for series 1, was plotted from the data of Table 2 and shows the loss under the conditions of the apparatus shown in Fig. 10. The upper curve, for series 2–13, was plotted from the data of Table 3. For some of these runs the length of eduction pipe was 19.32 feet, while during the others it was 26.74 feet, but the length of air pipe was constant. The middle curve, for series 14 and 15, was plotted from the data of Table 4. During these runs the length of eduction pipe was 41.50 feet, but the air pipe was shorter than during series 2–13. The length of air pipe was not measured, but it may be seen from the lower curve that the loss due to the foot-piece was considerable, as in the conditions of the tests represented by this curve, there was only one elbow and less than a foot of air pipe between the gage and the nozzle.

To compute the loss of pressure under operating conditions; that is, when discharging against the pressure p_i in the foot piece, it was assumed that fluid friction varies very nearly with the square of the velocity and directly with the density. If we let

p_a = the loss of pressure, in pounds per square inch, when discharging into the atmosphere,

p_x = the loss of pressure, in pounds per square inch, when discharging against the pressure p_i in the foot-piece,

v_a = the velocity of air in the pipe, in feet per second, when discharging into the atmosphere,

v_x = the velocity of air in pipe, in feet per second, when discharging against the pressure p_i,

q_a = the volume of free air discharged, in cubic feet per second,

q_x = the volume of air at pressure p_i, in cubic feet per second,

r = the ratio of compression in atmospheres,

the following proportion may be written

$$p_a : v_a^2 r_a :: p_x : v_x^2 r_x$$

Taking r_a as 1, when discharging into the atmosphere, we have

$$p_x = \frac{p_a v_x^2 r_x}{v_a^2} = \frac{p_a q_x^2 r_x}{q_a^2} = \frac{p_a \left(\frac{q_a}{r_x}\right)^2 r_x}{q_a^2} = \frac{p_a}{r_x}$$

Hence it was only necessary to divide the loss as taken from the curves in Fig. 19 by the ratio of compression, in order to find the loss of pressure when discharging against any pressure p_i existing in the foot-piece.

Loss of Head Due to Entrance.—The entrance to the tail-piece was square edged during the first 318 runs and the loss of head due to entrance was, therefore, assumed to have been equal to one-half of the velocity head of the entering water. The maximum value of the velocity head during this series of runs barely amounted to one per cent. of the total head required to discharge the water. During the 1909 experiments the tail-piece projected into the water and the entrance head has been assumed as equal to the velocity head of the entering water for these runs. The entrance head is therefore expresssd as

$$h_e = \frac{1}{2}\frac{v_t^2}{2g} \qquad \text{for flush entrance, and} \qquad (25)$$

$$h_e = \frac{v_t^2}{2g} \qquad \text{for inward projecting pipe} \qquad (26)$$

Loss of Head Due to Velocity of Discharge.—The velocity of discharge is much greater than the entrance velocity, due to the fact that the combined volumes of the water and air must be discharged through the outlet end of the pipe, while only the water enters the lower end. The loss due to the velocity of discharge is

$$\frac{v_b^2}{2g} = \frac{\left(\frac{q_w + q_a}{a_p}\right)^2}{2g} \qquad (27)$$

in which v_b = the outlet velocity, in feet per second.

q_w = the discharge of water, in cubic feet per second.

q_a = the discharge of free air, in cubic feet per second.

a_p = area of cross section of eduction pipe, in square feet.

Loss of Head Due to Elbow.—From experiments made in the Hydraulic Laboratory of the University of Wisconsin it was determined that the loss of head due to a 2-inch cast iron elbow was equal to *

$$H = 0.0202 \ v^2$$

or

$$H = 1.3 \frac{v^2}{2g}$$

and from comparison of these experiments with others on different sized pipes, it was concluded that the loss of head was independent of the size of pipe.† In estimating the loss due to the 1¼-inch cast iron elbow in the air lift experiments it has, therefore, been computed as 1.3 the velocity head of the discharge water, or

$$h_o = 1.3 \frac{v^2_o}{2g} \tag{28}$$

The loss of head caused by an elbow or bend is largely due to the eddies in the straight pipe following the elbow. The elbow at the top of the air lift pump used in the Wisconsin experiments was followed by only a few inches of straight pipe, so the above formula probably somewhat over estimates the elbow loss.

Loss of Head Due to Pipe Friction and Slip.—The loss of head in the straight part of the eduction pipe varies considerably with the amount of air used, due to the difference in the amount of slip of the water past the air at different velocities of discharge, but it was not possible to estimate the loss due to slip separately from the pipe friction. It was observed in the glass eduction pipe that in addition to the uniform gradual slip of the water past the air bubbles, there were at times sudden disturbances caused by a considerable quantity of water slipping down past a relatively large quantity of air. Loss is occasioned by the necessity of again lifting the water which has slipped down, and also by the internal friction due to the agitation of the water caused by the slip and by the pipe friction.

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* See discussion on curve resistance in water pipes, by Geo. Jacob Davis, Jr. in Trans. Am. Soc. C. E., Vol. LXII, p. 112. (1909).

† Ibid p. 109, effect of pipe diameter.

If h_a = the head produced by the air used per pound of water pumped,

h_p = the combined loss of head due to pipe friction and slip,

v_c = the velocity of the water in the well outside the eduction pipe at the elevation C in Fig. 3 p. 25.

and using the symbols already established for the the other quantities involved, the equation of energy per pound of water pumped, between the outlet and a point in the well outside the eduction pipe at the elevation C, may be written as follows:

$$\frac{v_c^2}{2g} + \frac{p_c}{u_w} + h_c + h_a = \frac{v_b^2}{2g} + \frac{p_b}{u_w} + h_b + h_e + h_o + h_p \qquad (29)$$

In computing the losses the velocity of approach has been neglected and the velocity v_c of the water in the well is taken as 0. To illustrate the method of computing the friction factor, the following data of run No. 338 will be used.

Length of eduction pipe = 19.32 feet.

Depth of submergence = 1.312 × 13.6 + 1.104 — 3.00 = 15.95 feet.

Diameter of tail-piece = 1½ inches, ∴ area = 0.01227 square feet.

Diameter of eduction pipe = 1¼ inches, area = 0.00852 square feet.

Length of pipe = 19.50 feet, including a short nipple at discharge end of eduction pipe, $\therefore \frac{l}{d} = 187$

Discharge of water = 0.0322 cubic feet per second, or 2.01 pounds per second.

Quantity of air used = 0.1111 cubic feet per second = 0.1111 ÷ 13.093 = 0.008481 pounds per second.

Total discharge, air and water = 0.1433 cubic feet per second.

Entrance velocity = v_t = 0.0322 ÷ 0.01227 = 2.62 feet per second.

Entrance velocity head = $\frac{v_t^2}{2g}$ = 0.106 feet.

Entrance loss of head = $\frac{v_t^2}{2g}$ = 0.106 feet.

Outlet velocity $= v_b = 0.1433 \div 0.00852 = 16.8$ feet per second.

Outlet velocity head $= \frac{v_b^2}{2g} = \frac{(16.8)^2}{64.32} = 4.389$ feet.

Elbow loss of head $= 1.3 \times 4.389 = 5.706$ feet.

Barometric pressure $= p_b = 28.95 \times 0.4912 = 14.22$ pounds per square inch.

Pressure in air pipe $= p_g = 1.376 \times 5.894 + 28.95 \times 0.4912 = 22.33$ pounds per square inch.

Pressure in foot-piece $= p_i = 22.33$ pounds per square inch minus loss in air pipe and nozzle. Loss when discharging into the atmosphere $= 1.36$ pounds per square inch (from curve Fig. 19). Loss when discharging against the pressure $p_i = 1.36 \div \frac{22.33}{14.7} = .897$ pounds per square inch. $\therefore p_i = 22.33 - .897 = 21.433$ pounds per square inch.

Energy per pound of air used $= 11{,}350$ foot pounds. (Curve Fig. 18.)

Weight of air used $= 0.008481$ pounds.

Energy of air used per second $= 11350 \times 0.008481 = 96.26$ foot pounds per second.

Energy of air per pound of water pumped $= h_a = 96.26 \div 2.01 = 47.89$ foot pounds.

Head due to atmospheric pressure $= 14.22 \times 2.308 = 32.82$ feet.

The pressure head $\frac{p_c}{u_w}$ was equal to the submergence plus the head due to atmospheric pressure. The datum plane was taken at C in Fig. 3 making $h_c = 0$. The values found above may be substituted in the energy equation as follows:

$0 + (15.95 + 32.82) + 0 + 47.89 = 4.389 + 32.82 + 19.32 + 0.106 + 5.706 + h_p$.

$$h_p = 34.32 \text{ feet.}$$

$$c_p = \frac{h_p}{\frac{l}{d} \times \frac{v_b^2}{2g}}$$

$$c_p = \frac{34.32}{187 \times 4.389} = .04181$$

In the manner above described the values of the friction factor c_p have been computed for most of the runs of series 1 and for a few runs in some of the other series. The results are given in column 14 of Table 1. These values of the friction factor have been plotted as ordinates against the velocities, designated as v_i, of the water in a 1¼-inch tail piece as abscissas. The velocities in a tail-piece of the same size as the eduction pipe were used instead of the actual velocities in the 1½-inch tail-piece, so as to make it possible to compare the values of c_p with the friction factors for unmixed water flowing in a pipe of the same size as the eduction pipe. In Fig. 20 the numbers adjacent to the points indicate the ratio of volume of free air used to volume of water pumped for each run. Curves have been sketched in to indicate the relation between c_p and v_i for given ratios of air to water. Before the regular runs were begun on the air lift, a number of runs were made with no air, for the purpose of determining the normal pipe friction in the eduction pipe, which, it will be remembered, was largely made of glass. The friction factors computed from these preliminary runs are also plotted on Fig. 20. It may be seen in this figure that these normal friction values agree very closely with the values computed from Fanning's table of friction factors for clean iron pipe. It may also be seen that when pumping with air the friction factors are very much larger than when only water is flowing through the pipe, but the value of c_p does not increase with the ratio of air to water but instead it rapidly decreases as the ratio increases from small values, apparently reaching a minimum value when an excessively large amount of air is used. This may be due to the fact that when very small amounts of air are used, the air bubbles rise through the water without causing much discharge, the energy of the air being mostly used up in causing eddies in the water in the pipe.

The value of the friction factor, computed as described above, seems to be entirely independent of the percentage of submergence and of the lift. The values, however, decrease with the length of pump, which may be seen by reference to Fig. 20, the points for the 26.74-foot length falling a small

distance below the curves, while the points for the 41.50-foot length fall a relatively larger distance below the curves. The curves shown in Fig. 20 are therefore of no practical importance, and it would seem that for a theoretical design of an air lift pump, the law of variation of c_p with both the diameter and length of pump would have to be known.

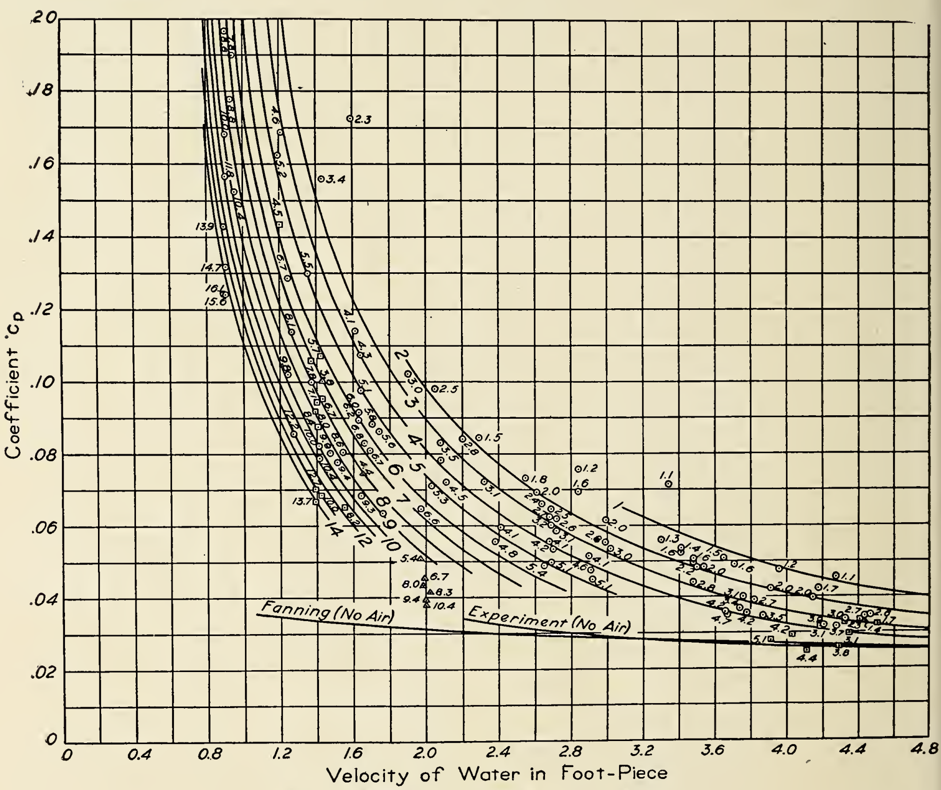


Fig. 20.—Coefficient of Pipe Friction and Slip.

⊙ = Length of Pump 19.32 Feet

⊡ = " " " 26.74 "

△ = " " " 41.50 "

EXPERIMENTAL RELATIONS

The experiments made by the writers were planned to determine, first, the effect on the discharge and efficiency of variations in the working conditions of the air lift pump, such as variations in submergence, lift and quantity of air used, and second, the effect on the discharge and efficiency of changes in the structural features of the pump. The first part of the following discussion relates to experiments in which all structural features were the same.

Relation of Discharge to Air Used

The relation between the quantity of air used and the quantity of water pumped is shown in Fig. 21 for each of the runs of the first series. The small figures, by the plotted points, indicate the percentage of submergence obtaining during the run represented by the point. Curves have been interpolated between the points to indicate the discharge of the water for varying quantities of air under constant conditions of submergence and lift, for each five per cent. submergence from 35 to 115 per cent. These curves were first sketched in freely, interpolating by eye to locate their positions, and were afterwards adjusted to harmonize with the curves in Fig. 22. Each of these curves was plotted by reading horizontally across Fig. 21 the percentage of submergence corresponding to given quantities of air for a constant discharge of water. The trial curves in Fig. 21 were then shifted slightly until the points picked from them fell on smooth curves in Fig. 22.

Fig. 21 shows that for any given percentage of submergence an increase in the amount of free air used, starting with zero quantity, causes an increase in the discharge of water up to a given quantity of air, beyond which the discharge of water decreases with a further increase of air. The quantity of air giving a maximum discharge of water is not a constant for the different percentages of submergence, nor is the ratio of the volumes of air and water constant for the maximum discharge

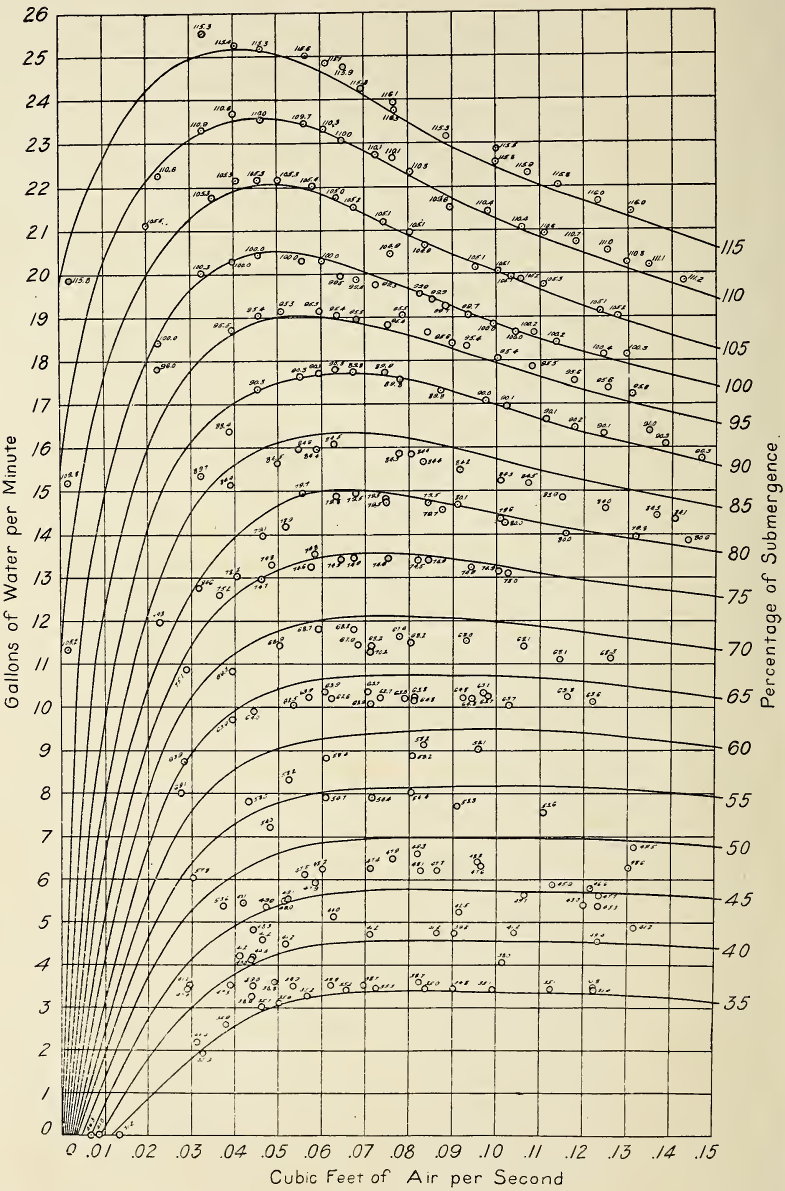


Fig. 21.—Relation of Discharge to Air Used.—Series 1.

at different percentages of submergence. The quantity of air giving the maximum discharge is less, both absolutely and relatively, for high percentages of submergence than it is for low percentages of submergence.

From the curves of Figs. 21 and 22, it appears that for any given rate of air consumption, the discharge of water increases indefinitely as the percentage of submergence increases In this connection these curves are likely to be misleading unless the conditions of the experiments are borne in mind. All of the experiments represented by the points in Fig. 21 were made with a constant length of pump of 19.32 feet. Therefore, an increase in the submergence was necessarily accompanied by a decrease in the lift, the latter becoming zero at 100 per cent., and negative at higher percentages of submergence. That is, at percentages greater than 100 per cent. there was a head on the outlet of the pump which caused a flow without the use of any air, as in the case of artesian wells. In commercial plants using the air lift system of raising water, the pump is of fixed length designed and built to work at some definite percentage of submergence. In many cases the water level in the well is not correctly estimated for working conditions, or the conditions existing at the time of installing the well may be changed by the operation of other wells in relatively close proximity, so that it is often found that the relation of lift to submergence in the case of many pumps is far from what it should be. The large variations in the discharge which may result from such changes in the percentage of submergence are clearly indicated in Figs. 21 and 22.

Relation of Output to Percentage of Submergence

As to the question of what is the best percentage of submergence to adopt in the design of a pump to lift the water a definite height, no information is given in Fig. 21, for the reason that it is impossible to determine from this diagram whether the increased discharge of water is due to the increase in the percentage of submergence or to the accompanying decrease in the lift.

In order to throw more light on this subject Figs. 23, 24 and

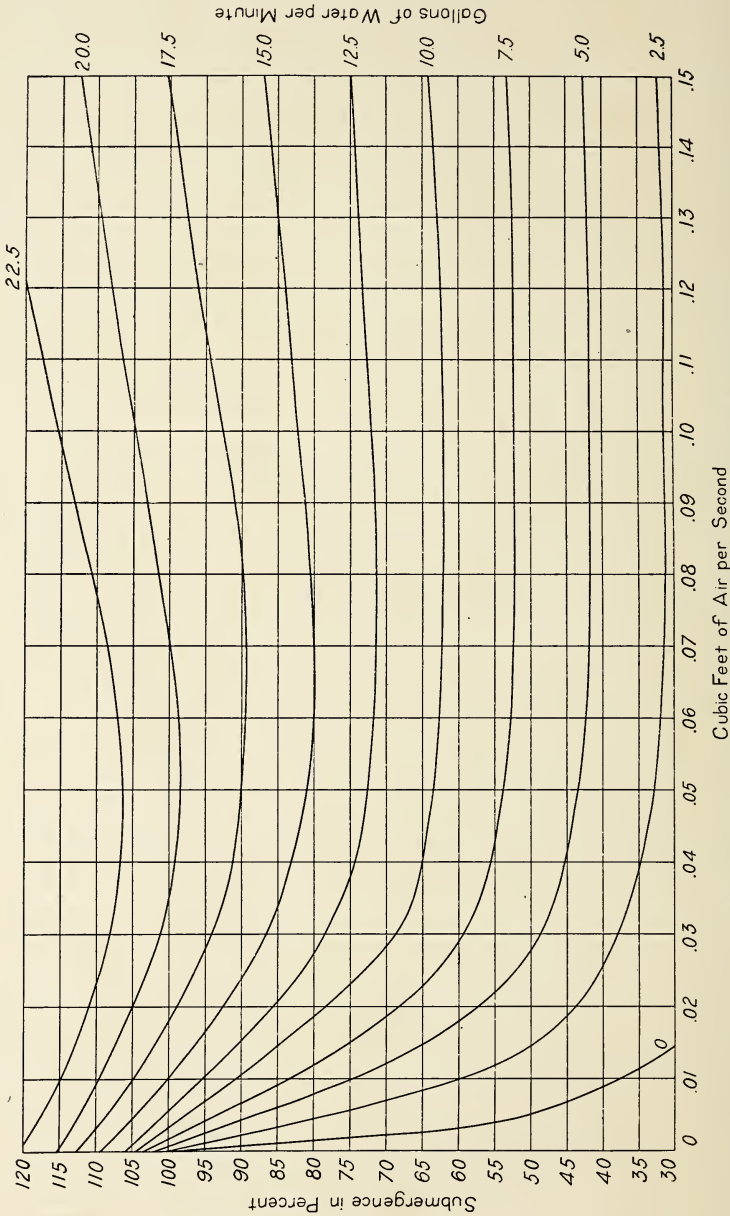


Fig. 22.—Relation of Air Used to Percentage of Submergence.—Series 1.

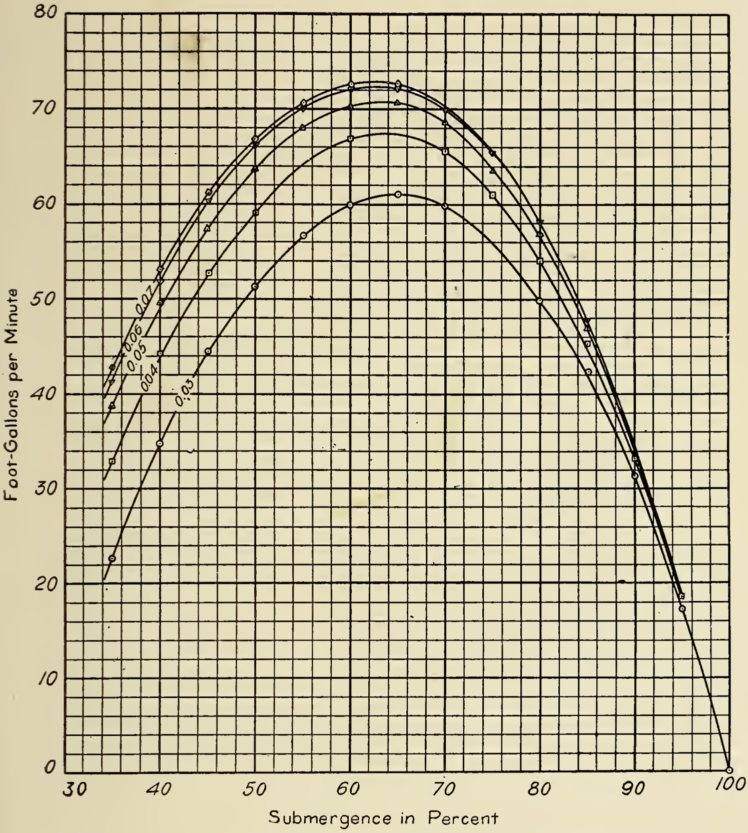


Fig. 23.—Relation of Output to Percentage of Submergence.—Series 1.

25 have been plotted. The method of constructing these curves is as follows: Choosing some definite rate of air consumption, as for example 0.03 second feet, and reading vertically along this air line in Fig. 21. the discharges were obtained for each five per cent. submergence. These quantities were then multiplied by the lift in feet for the corresponding submergences. This gave the work output, expressed in foot gallons, for each five per cent. submergence. In order to avoid confusion, part of the curves, those for the rates of air from 0.03 to 0.07 second feet have been plotted in Fig. 23 and the remainder in Fig 24. The curves are shown only as far as 100 per cent. submergence.

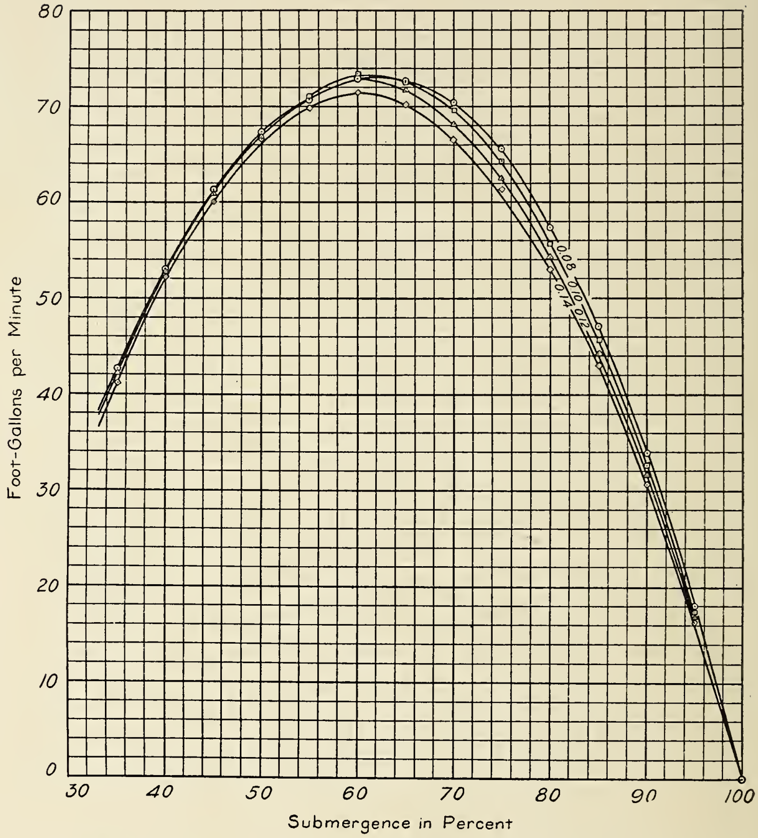


Fig. 24.—Relation of Output to Percentage of Submergence.—Series 1.

Beyond that limit the output is negative on account of the lift being negative, and the curve extends in the general direction indicated by the part near the 100 per cent. submergence point. In-as-much as the discharge increases from zero, while the lift decreases from a maximum value to zero as the percentage of submergence increases, there is necessarily a maximum point on the curve. The maximum points for all the curves lie between 60 and 65 per cent. submergence. The percentage of submergence giving the maximum output is shown for various rates of air consumption by the curve in Fig. 25. In this figure is shown also the relation between air consumption and maximum output.

By inspection of these two curves it may be seen that the maximum output occurred when the rate of air consumption was about 0.09 second feet and the percentage of submergence was about 61. Since the lift corresponding to 61 per cent. submergence was 7.55 feet, the maximum output of 73.2 foot gallons represented a discharge of 0.0215 second feet of water.

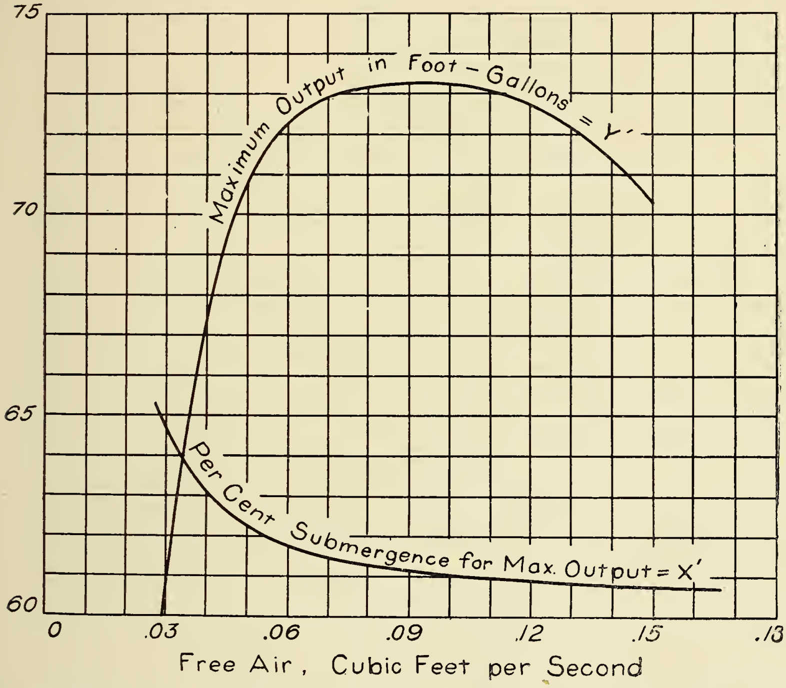


Fig. 25.—Relation of Quantity of Air Used to Maximum Output and to Percentage of Submergence.—Series 1.

Hence, for maximum output the ratio of volumes of air to water was $0.09 \div 0.0215 = 4.2$. The curves are based on experiments on a single length of pump of 19.32 feet. Some experiments on pumps of different lengths show that for the same air consumption and percentage of submergence the output increases with the length of pump, therefore the outputs in foot gallons shown on Figs. 23, 24 and 25 must be regarded as applying only to the 19.32-foot pump. The experiments on the longer pumps were taken at only two submergences, of ap-

proximately 40 and 80 per cent., so curves similar to those of Figs. 23 and 24 could not be drawn for the longer pumps; but the points for these runs plot in such a way as to indicate that the maximum point must be about the same percentage of submergence as for the shorter pump.

The curves of Figs. 23 and 24 seem to be parabolas having the equation

$$(y - y') = m \ (x - x')^n \qquad (30)$$

in which

$y =$ the output in foot gallons.

$y' =$ the maximum output in foot gallons.

$x =$ submergence in per cent.

$x' =$ submergence in per cent. corresponding to maximum output.

By taking the values of x' and y' for any given value of air from Fig. 25, and subtracting them from the values of x and y taken from the curves of Fig. 23 for the same value of air, the values plotted in Fig. 26 were obtained. The symbols with horizontal bars attached represent points of the curve on one side of the vertex while the plain symbols represent points on the other side of the vertex on the same curve. The points near the lower end of the diagram scatter somewhat. These points correspond to points very near the vertex of the parabolas and the divergence from the mean line simply indicates a very small error in the values of x' and y', which were found by trial. The substantial agreement of the points with the line shows that for the 19.32-foot pump, the output varies in accordance with the parabolic law and that for all rates of air consumption the values of m and n are the same. Using the values of m and n determined from the mean line of Fig. 26 the equation of the curves becomes

$$y - y' = 0.028 \, (x - x')^{2.15} \qquad (31$$

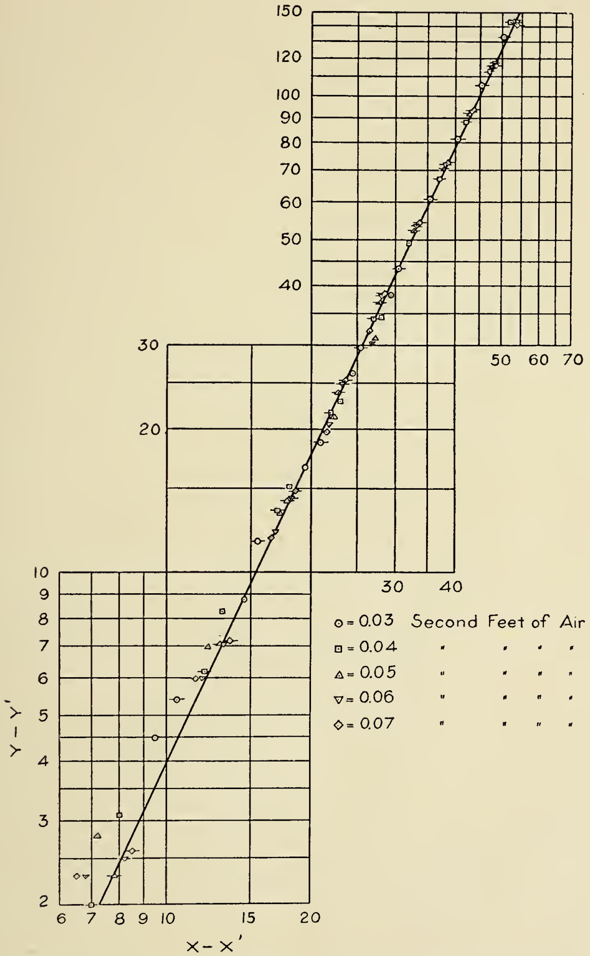


Fig. 26.—Logarithmic Plotting of Output—Percentage of Submergence Curves.—Series 1.

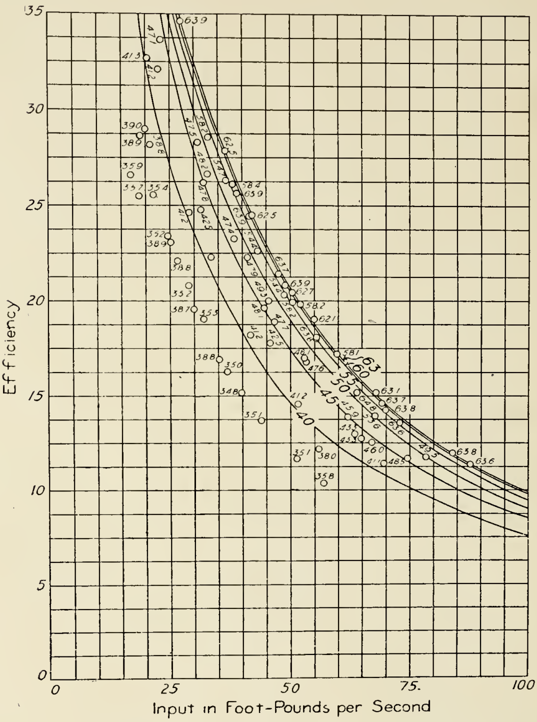


Fig. 27.—Relation of Efficiency to Input with Constant Length of Pump. Runs (1-86) Series 1.

Relation of Efficiency to Input and Percentage of Submergence with Constant Length of Pump

If the quantity of free air used were a measure of the work input then the curves of Figs. 23, 24 and 25 would show the submergence to adopt for maximum efficiency at any given rate of air consumption, but such is not the case. An increase in the percentage of submergence, in the case of a pump of fixed length, results in a greater depth of submergence of the air inlet and consequently in an increased air pressure. With a constant consumption of free air the work input varies with the submergence. In order to show the effect of variations in the submergence and input on the efficiency of operation the curves in Figs. 27, 28 and 29 have been drawn.

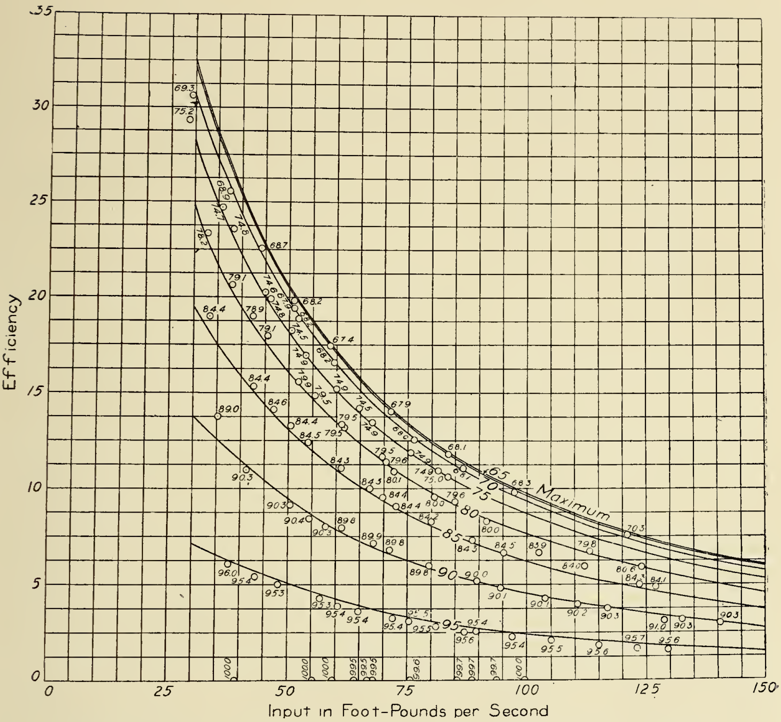


Fig. 28.—Relation of Efficiency to Input with Constant Length of Pump. Runs (87–202) Series 1.

Efficiency and Input.—The efficiencies computed from runs (1—202) of the first series of experiments have been plotted as ordinates against the corresponding inputs in Figs. 27 and 28. In order to avoid confusion of lines the points with percentages of submergence lower than 63 were plotted in Fig. 27 and those above were plotted in Fig. 28. These curves show that for any given constant percentage of submergence and constant length of pump, the efficiency increases very rapidly as the input decreases. Efficiencies higher than those shown on the diagrams have only slight practical importance on account of the small discharge of water obtainable when working at such low rates of input, and the consequently high initial cost of the well in proportion to the discharge.

Efficiency and Percentage of Submergence.—The curves in Figs. 27 and 28 also show that, if the total length of eduction pipe remains constant, the maximum efficiency for a given input or rate of pumping is obtained at about 63 per cent. submergence. This is more clearly shown in Fig. 29, which was drawn from values taken from the average curves of Figs. 27 and 28. It will be seen from these diagrams that with a given input,

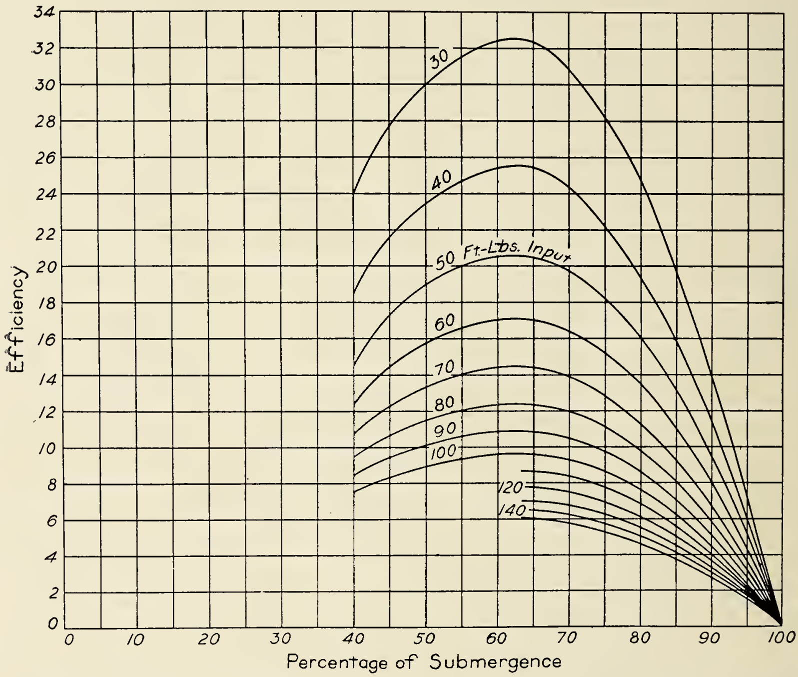


Fig. 29.—Relation of Efficiency to Percentage of Submergence with Constant Length of Pump.—Series 1.

the efficiency first increases with the percentage of submergence until a maximum is reached at about 63 per cent., and then decreases with a further increase in the percentage of submergence; becoming zero at 100 per cent. submergence and the efficiencies having negative values when the percentage of submergence is greater than 100, because for such cases the lift has a negative value. The efficiency curves are not drawn for submergences greater than 100 per cent. The total length

of eduction pipe, however, remaining constant, the lift varies as the percentage of submergence is changed.

Relation of Efficiency to Input and Percentage of Submergence With a Constant Lift

In comparing the results of the Wisconsin experiments there are five variables to be considered; namely, the lift, the submergence, the discharge, and the quantity and pressure of the air used. In the previous discussion the effect of varying some

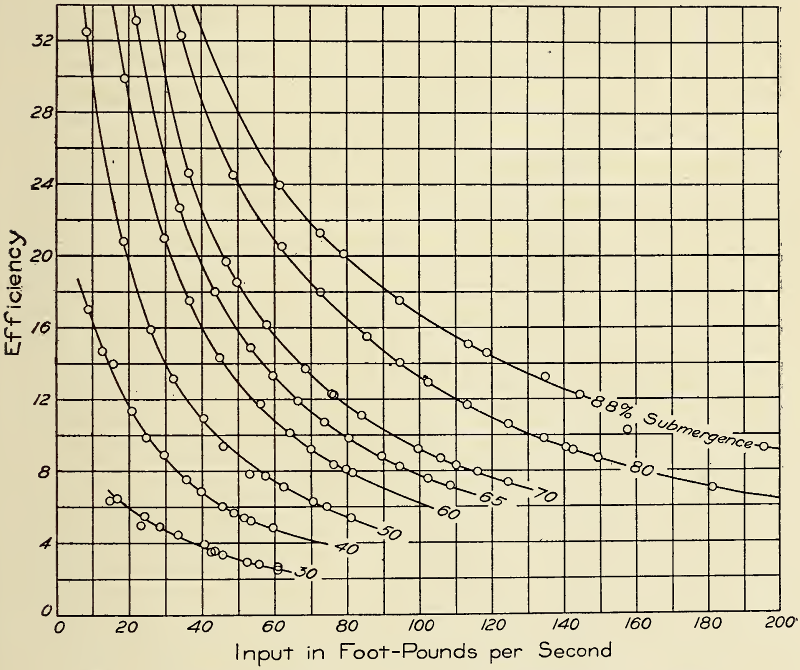
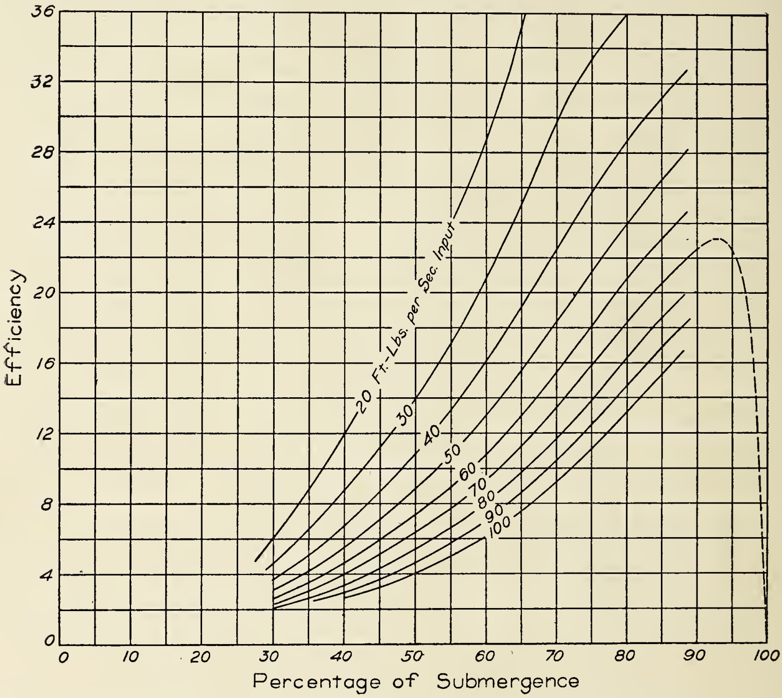


Fig. 30.—Relation of Efficiency to Input with a Constant Lift.—Series 20.

of these factors has been shown, but on account of the fact that the lift varied inversely as the submergence, the methods of comparison used on the preceding pages do not give definite information as to the best submergence to use with a constant lift. The practical problem in most deep well propositions is to determine at what percentage of submergence the maximum efficiency will be obtained for a given lift. The curves of

Figs. 30 and 31, plotted from the data of series 20, show this information. In this series the lift was kept constant at five feet and the percentage of submergence was varied by changing the length of pump.

Efficiency and Input.—Fig. 30 shows that for any given constant percentage of submergence and constant lift, the effi-



Fif. 31.—Relation of Efficiency to Percentage of Submergence with a Constant Lift.—Series 20.

ciency increases as the input decreases, which checks the conclusion drawn from the curves of Figs. 27 and 28.

Efficiency and Percentage of Submergence.—Fig. 30 also shows that with a constant lift, the efficiency increases as the percentage of submergence increases, for all rates of input and all practical percentages of submergence. This result is quite different from that obtained when the length of pump remained constant and lift varied, as may be seen by comparing the curves of this figure with those of Figs. 27 and 28. The above

conclusions may perhaps be more plainly seen by reference to Fig. 31, which was plotted for the purpose of comparison with the curves of Fig. 29. The curves of Fig. 31 show a tendency to reverse after passing the ordinate at 90 per cent. submergence. This may be understood if one reflects that between 90 and 100 per cent. the length of pump increases very rapidly with any constant lift, reaching infinity at a submergence of 100 per cent. Hence, the efficiency will decrease very rapidly as the percentage of submergence is increased from a point near 90 per cent. submergence to a submergence of 100 per cent., as indicated by the broken curve for an input of 70 foot pounds.

Relation of Discharge and Efficiency to Lift

In discussions of the air lift the statement is frequently made that an increase in the lift causes a reduction in the discharge and in the efficiency, other conditions remaining constant. That this statement is not true in all cases is proved by the curves shown in Fig. 32, in which are plotted the results of three series

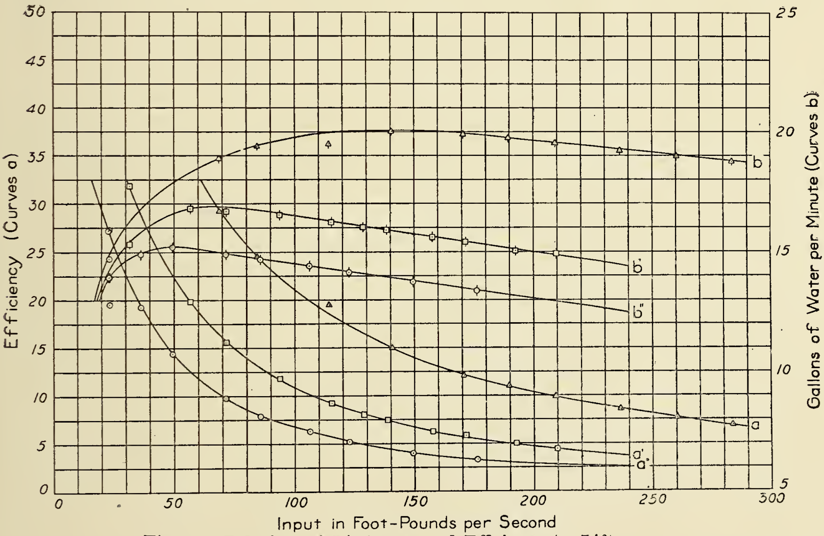


Fig. 32.—Relation of Discharge and Efficiency to Lift.

○ = Series 4—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 3.29 Feet—Average Submergence 82.97 Per Cent.
□ = Series 11—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 26.74 Feet—Average Lift 4.74 Feet—Average Submergence 82.40 Per Cent.
△ = Series 14—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 41.50 Feet—Average Lift 7.66 Feet—Average Submergence 81.54 Per Cent.

of experiments made in order to show the effect of varying the lift, other conditions remaining the same. The same foot-piece and size of eduction pipe were used in all these series, the submergence was kept nearly constant, at about 82 per cent., and the lift was varied by adding extra pipe to the discharge end of the eduction pipe. This diagram shows, that for a given input, the discharge and hence the efficiency, increases with the lift and the length of eduction pipe; the percentage of submergence and all other conditions, except the length of the pipe, remaining constant.

A similar result was obtained at a smaller percentage of submergence, as is shown in Fig. 33. In this diagram the dis-

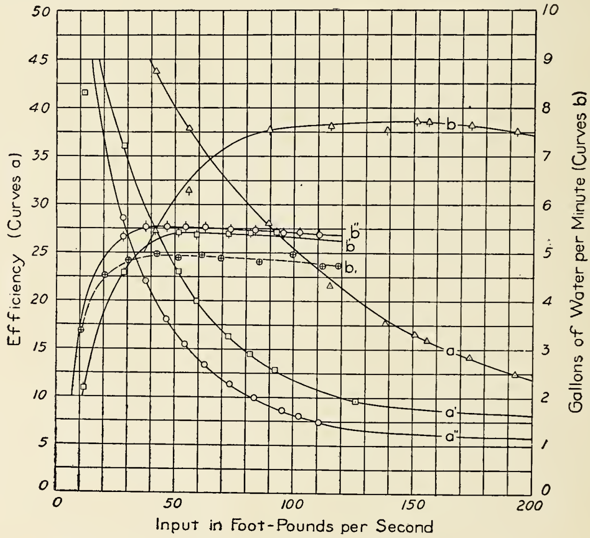


Fig. 33.—Relation of Discharge and Efficiency to Lift.

⊙ = Series 7—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 10.88 Feet—Average Submergence 43.66 Per Cent.
⊡ = Series 10—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 26.74 Feet—Average Lift 15.73 Feet—Average Submergence 41.19 Per Cent.
△ = Series 15—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 41.50 Feet—Average Lift 23.47 Feet—Average Submergence 43.45 Per Cent.
⊕ = Series 6—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 11.40 Feet—Average Submergence 40.97 Per Cent.

charge curve for a lift of 15.73 feet lies below that for a lift of 10.88 feet, although for a given input the efficiency is greater for the larger lift. This apparent disagreement with the law seeming to hold for the other series of runs plotted, was doubt-

less due to the fact that the percentage of submergence was different in the two series of runs. It was difficult in setting up the apparatus and adjusting the valves to get exactly the same percentage of submergence in the different series, or even to maintain the percentage constant for all the runs of a series. To show the difference in the discharge due to the variation in the percentage of submergence the discharges for series 6 have been plotted in Fig. 33 and a dash line has been drawn through them. The average percentage of submergence for these runs was 40.97 and the lift 11.40 feet. By comparing this curve with that for series 10, which was made with practically the same percentage of submergence, it may be seen that the discharge with the higher lift of 15.73 feet was considerably greater than the discharge with the lift of 11.40 feet. The discharge curve for the 15.73-foot lift would therefore have plotted higher, between the curves for the 10.88-foot and the 23.47-foot lifts, if the conditions of submergence had been the same in the three series of runs.

The reason for an increase in the discharge occurring when the length of pump is increased may be understood by studying the theoretical relations of the various quantities involved, as expressed in equation (17) of the Lorenz theory (see p. 28). By transposing this equation and restoring u_b which had been cancelled out from equation (12) it may be made to read

$$q_w = \frac{\left(2.303 \frac{p_b}{u_b} \log_{10} \frac{p_i}{p_b}\right) q_b u_b \frac{2g a_p^2}{u_w}}{2gh_l a_p^2 + \left(1 + c_p \frac{l}{d}\right)\left(q_b + q_w\right)^2 + c_e q_w^2} \qquad (32)$$

To adapt this formula to the conditions of the Wisconsin experiments, 1.3 must be added to the quantities in the first parenthesis of the denominator to take account of the loss due to the elbow at the top of the eduction pipe. With this change, equation (32) becomes

$$q_w = \frac{\left(2.303 \frac{p_b}{u_b} \log_{10} \frac{p_i}{p_b}\right) q_b u_b \frac{2g a_p^2}{u_w}}{2gh_l a_p^2 + \left(2.3 + c_p \frac{l}{d}\right)\left(q_b + q_w\right)^2 + c_e q_w^2} \qquad (33)$$

Curves showing the relation of the discharge, q_w, to the lift,

h_1, have been computed by means of this formula for three different percentages of submergence, and are plotted in Fig. 34. The conditions assumed were as follows:

Area of eduction pipe = 0.00852 square feet.

Percentages of submergence = 40, 60, and 80 per cent.

Barometric pressure = 14.3 pounds per square inch. (The approximate average pressure during series 1.)

Input at piezometer on air pipe = 100 foot pounds.

In the numerator of equation (33) the expression

$$q_b\, u_b \left(2.303\, \frac{p_b}{u_b} \log_{10} \frac{p_i}{p_b}\right)$$

represents the input at the air inlet in the foot-piece. In the 1909 experiments the pressure, from which the input was computed, was measured at a point on the air pipe some distance from the foot-piece. The pressure, so measured, therefore, includes the loss in a section of air pipe of length sufficient to reach from the top of the well to the foot-piece. This loss should be charged to the pump, for such a length of air pipe is inevitable. Hence, in computing the quantity of air used at any given rate of pumping and at any lift, the gage pressure, p_g, should be used instead of the pressure, p_i, in the foot-piece.

Putting $q_b\, u_b \left(2.303\, \frac{p_b}{u_b} \log_{10} \frac{p_g}{p_b}\right) = 100$, the assumed input, the quantity of air used per second was computed for the gage pressures corresponding to the various lifts and percentages of submergence. The gage pressure, p_g, was computed, for the assumed conditions, by adding 14.3 pounds per square inch, to 0.434 times the depth of submergence in feet, plus the loss of head due to friction in the air pipe and nozzle, minus the loss due to entrance and velocity in the foot-piece. Since the loss of head due to friction in the air-pipe and nozzle is a function of the volume of air used, it was necessary to first assume the volume of air in order to estimate the approximate loss of head due to air friction from the curve of Fig. 19 as explained on page 75. By making a few approximations in this way, the proper value of p_g and the corresponding value of q_b were found. An assumed value of the discharge q_w was used to com-

pute the ratio of volume of free air to volume of water and the ratio of discharge to area of eduction pipe which were used as arguments in estimating the friction factor c_p from Fig. 20. By making a few such approximations, corresponding values of c_p, q_a, and q_w were found which satisfied equation (33).

With constant percentage of submergence, an increase in the lift causes a proportionate increase in the depth of submergence and, therefore, a proportionate increase in the pressure. As the air pressure increases with the lift, the quantity of free air per given input will decrease as the lift increases. The

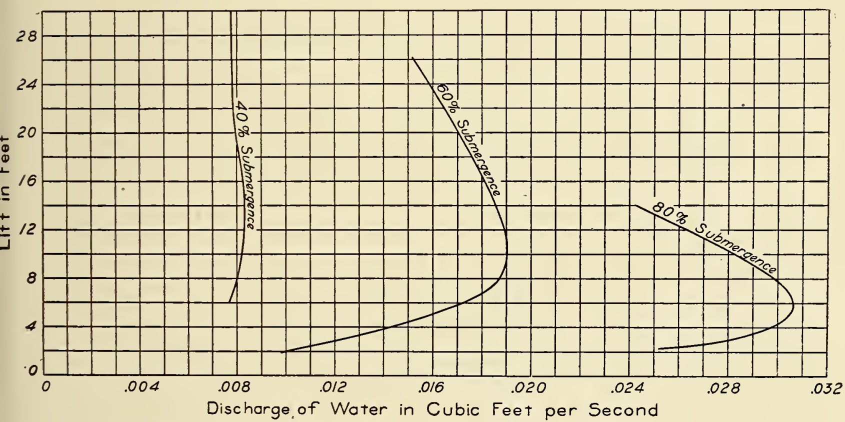


Fig. 34.—Relation of Discharge to Lift with Constant Input.

numerator of equation (33), therefore, increases slightly as the lift increases, because the loss in the air pipe is less with the smaller volume of air and consequent lower velocity. Also, since q_w is small compared with q_b, an increase in the lift decreases the value of the second parenthesis in the denominator of equation (33). c_p varies with the velocity of the water in the foot-piece and with the ratio of volume of free air to volume of water. It was found, in computing, that the relation of these quantities was such as to make c_p increase with the lift and that the last term in the denominator, which is a function of the entrance loss, was practically negligible. The middle term of the denominator proved to be the controlling one in the determination of the shape of the discharge-lift curve.

With the first parenthesis increasing in value and the second decreasing with the lift, evidently their product must have a maximum value at some point. The points of maximum discharge, as shown by the curves of Fig. 34, do not agree with the indications of Figs. 32 and 33, which show the discharge increasing up to higher lifts. This discrepancy is explained by the fact that for a given velocity of water in the foot-piece and given ratio of volumes of air to water the friction factor c_p decreases with the length of pump, as pointed out on page 79. In-as-much as the law of this variation is not known, the value of c_p was necessarily assumed independent of the lift, and in making the computations the values were taken from the curves of Fig. 20. It may be seen, however, by reference to equation (33), that if c_p decreases with the lift, other things being constant, the maximum discharge would have occurred at a higher lift under the assumed conditions and the curves of Fig. 34 would have tended to check the experimental results.

Effect of Compressed Air Outside of Pump

When the Harris foot-piece was purchased the manufacturers furnished it with fittings for introducing compressed air into the well casing outside of the pump, but the apparatus as used in the 1908 experiments did not permit any runs under these conditions. The statement is made in the Harris patent (No. 758360) that "the chief feature consists in combining the idea of introducing compressed air or gas into the casing to act upon the surface of the water or other fluid to force the same downward and the use of a suction means, such as an ejector or similar means, for drawing up the fluid and expelling it." Through correspondence we were informed by the manufacturers of the Harris pump that "the object in the use of this outside pressure is to steady the flow of water and retard the usual surging up and down occasioned when air is liberated in the well. The idea is not to put on excessive pressure, and as to the amount of pressure to be used, it depends entirely upon conditions and necessarily has to be adjusted on the ground to meet the conditions encountered." They further stated in this connection that "we find in many cases that by

simply filing a leakage screw allowing a small volume of air to leak into the casing that it affords sufficient amount to work in harmony with the air pressure leading directly to the pump, while in other cases we find that it is often necessary to carry 25 or 30 pounds on the outside in order to assist in forcing the water through the discharge pipe."

In view of the foregoing it was deemed desirable to make

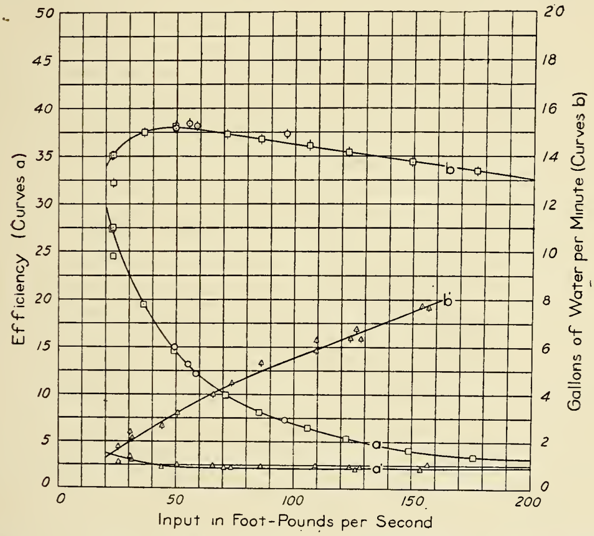


Fig. 35.—Curves Showing the Effect of Compressed Air Outside of Pump.

○ = Series 3—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 3.44 Feet—Average Submergence 82.19 Per Cent.—Compressed Air in Casing Connected with Air Main.

□ = Series 4—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 3.29 Feet—Average Submergence 82.97 Per Cent.—Compressed Air in Casing Shut Off from Air Main.

△ = Series 5—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 3.02 Feet—Average Submergence 84.37 Per Cent.—Annular Air Tube System.

some experiments with compressed air outside of the pump, and the apparatus as set up for the 1909 experiments was arranged with this object in view. Series 3, 4, 6, 7, 8, 9 and 10 were made for this purpose. The results are plotted in Figs. 35, 36 and 37, which show the efficiency and discharge curves for different rates of energy input under different conditions as to air outside of the pump. In series 3 the air was introduced above the surface of the water in the well and was

in connection with the air main throughout the run, the valve in the casing air pipe (see Fig. 15) being open, so that the air pressure in the casing remained constant, and in case of any leakage from the casing or connections the amount lost was included in the amount of air recorded as supplied to the pump. In series 4 the air was admitted through the casing air pipe to the surface of the water in the well before the run started, and after the proper submergence was obtained and the pump was working steadily the air in the casing was shut off from the main by closing the valve in the casing air-pipe. In case of any air-leakage under these conditions the water rose in the well, thereby keeping the submergence fairly constant during the run. By means of a glass gage connecting with the well near the top and bottom, marked well gage in Fig. 15, the elevation of the water in the well could be noted. During series 3 and 4 the water level in the well stood at times at various elevations lower than the air inlet, but during none of the runs did the water surface fall low enough to allow air to enter the bottom of the tail-piece. The submergence in both cases remained practically constant and there was no appreciable leakage from the casing. The points belonging to the two series of runs lie on the same curve in Fig. 35, indicating that there was no difference in the discharge under the two conditions, as was to be expected.

In the same figure the efficiency and discharge curves are plotted for series 5. In this series the same apparatus was used but the supply to the Harris foot-piece was shut off, the foot-piece, however, remaining in the well and the well pumped according to the annular air tube system described on page 34, all the air used entering through the casing air pipe. As may be seen from the diagram the efficiency for this method of pumping is very low, but this series of runs, however, should not be taken as a criterion for the efficiency of the annular tube system, as the apparatus was not properly designed for this system of pumping. Obviously the annular space between the 1¼-inch discharge pipe and the six inch casing was too large for efficient pumping.

Fig. 36 shows the results of series 6 and 7. In both series

the length of eduction pipe was 19.32 feet and the 1¼-inch Harris foot-piece was used. In series 6 the casing was open to the atmosphere so that the submergence was due entirely to the water in the well, while in series 7 compressed air was introduced above the surface of the water in the well and was shut off from the air main. It will be noticed, however, that the average submergence differed by 2.69 per cent., which un-

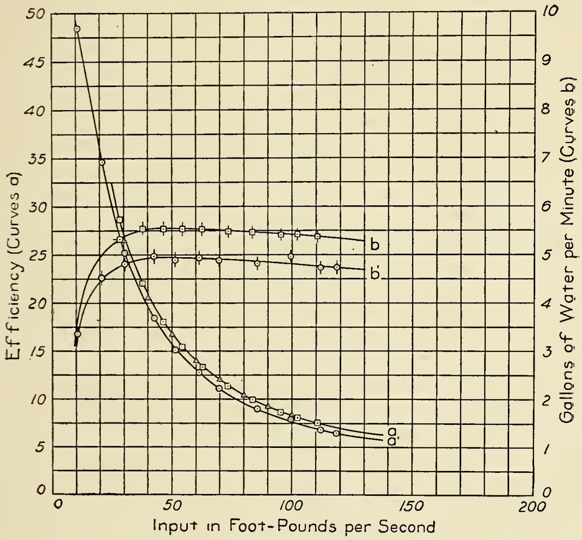


Fig. 36.—Curves Showing the Effect of Compressed Air Outside of Pump.

○ = Series 6—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 11.40 Feet—Average Submergence 40.97 Per Cent.—Casing Open to Atmosphere.

□ = Series 7—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 10.88 Feet—Average Submergence 43.66 Per Cent.—Compressed Air in Casing Shut Off from Air Main.

△ = Series 1—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 19.32 Feet—Average Lift 10.88 Feet—Average Submergence 43.66 Per Cent.—Submergence Obtained by Means of Overflow Hose Shown in Fig. 3.

doubtedly accounts for the higher efficiency for the higher percentage of submergence. In order to show what difference the percentage of submergence makes, the points plotted as triangles were interpolated from the curves shown in Fig. 27 for a submergence of 43.66 per cent. The curves in Fig. 27 were plotted from the first series of experiments in which the length of eduction pipe and foot-piece were the same as used in the series under discussion, but the submergence was obtained by

means of the overflow hose shown in Fig. 10 corresponding very closely to the conditions of series 6. As will be noticed from the diagram, the points fall very closely on the curve so that the conclusion may be drawn that had the percentage of submergence remained constant no difference would have been noticed in the efficiencies of the two series of runs. With the

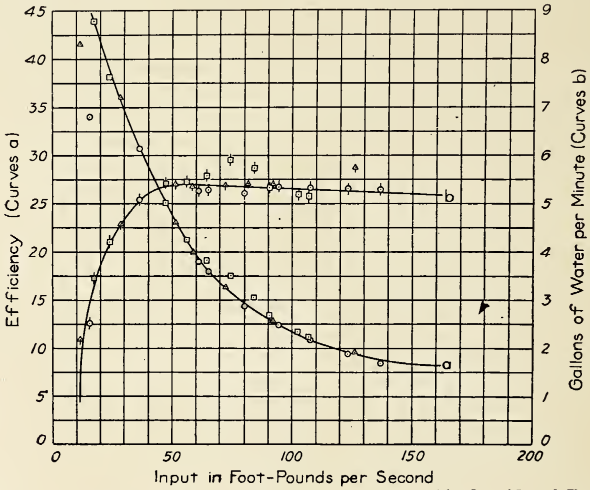


Fig. 37.—Curves Showing the Effect of Compressed Air Outside of Pump.

⊙ = Series 8—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 26.74 Feet—Average Lift 15.70 Feet—Average Submergence 41.29 Per Cent.—Casing Open to Atmosphere.

⊡ = Series 9—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 26.74 Feet—Average Lift 16.02 Feet—Average Submergence 40.08 Per Cent.—Compressed Air in Casing Connected to Air Main.

△ = Series 10—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 26.74 Feet—Average Lift 15.73 Feet—Average Submergence 41.19 Per Cent.—Compressed Air in Casing Shut Off from Air Main.

same size and length of pump and the same percentage of submergence, the discharge per given input would necessarily be equal for the two series, if the efficiencies were equal.

This conclusion is further justified by a study of Fig. 37. In this figure the results of three series of runs have been plotted, which differ only in the method of obtaining the submergence, the length of eduction pipe being 26.74 feet and the same size and style of foot-piece being used for the three series. The submergences remained more nearly constant in this case than in the preceding one, and the points are seen to lie very nearly on the same curve. In view of the results of these series of

experiments the conclusion seems justified that, other conditions remaining constant, there is no advantage to be gained by introducing compressed air above the surface of the water in the well.

Effect of Type of Foot-Piece

Figs. 38 and 39 were plotted from results of comparative tests on three different types of foot-pieces. The three different types used were the Harris, the Indiana, and a Tee pump which are shown in section in Figs. 11 and 12, and are described on page 57. The conditions during the different tests were kept as constant as possible, although, as previously stated, it was difficult to maintain the percentage of submergence the same for the different series. Fig. 38 shows the results of three series at a submergence of about 42.5 per cent. The highest efficiency for a given input is obtained either by the Tee or Indiana pump. The points for the Indiana series do not lie on a smooth curve, so no curve was drawn for this series, but they will average pretty close to the line drawn for the Tee pump. The percentages of submergence for the Indiana and Tee pumps were practically the same, while the percentage for the Harris pump was about 1 per cent. higher. This higher percentage of submergence was, however, in favor of the Harris pump, which may be seen by reference to Fig. 27.

In Fig. 39 are shown the results of three series of runs with the same foot-pieces, but at a higher percentage of submergence than shown in the preceding figure. It will be seen from this figure that the highest efficiency for a given input is obtained by the Indiana pump. The percentages of submergence for the Harris and Indiana pumps are nearly the same with the difference in favor of the Harris pump. The percentage of submergence for the Tee pump is, however, 2.2 per cent higher than the Indiana pump. Correcting for this difference would make the efficiency curve of the Tee pump coincide very nearly with that of the Indiana pump. The conclusion to be drawn from the curves shown in Figs. 38 and 39 is that both the Indiana and Tee pumps showed a slight advantage over the Harris pump, while the Indiana and Tee pump showed practically the

same efficiency, as nearly as could be seen from the curves. It should, however, be said in favor of the Harris pump that the Indiana pump was a 1½-inch foot-piece which was reduced to 1¼-inch at the entrance to the eduction pipe.

The opinion of the writers on this point is that the type of foot-piece has very little effect on the efficiency of the pump, so long as the air is introduced in an efficient manner and the full cross-sectional area of the eduction pipe is realized for the passage of the water. Anything in the shape of a nozzle to increase the kinetic energy of the air is detrimental.

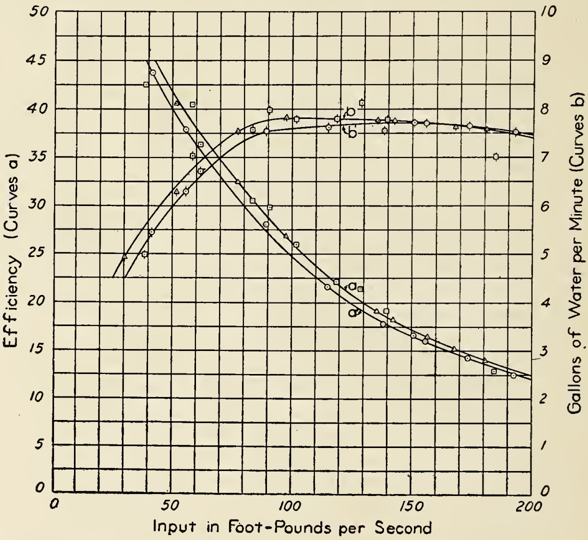


Fig. 38.—Curves Showing the Effect of the Type of Foot-Piece.

⊙ = Series 15—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 41.50 Feet—Average Lift 23.47 Feet—Average Submergence 43.45 Per Cent.

⊡ = Series 16—1¼-Inch Indiana Foot-Piece—Length of Eduction Pipe 42.08 Feet—Average Lift 24.20 Feet—Average Submergence 42.50 Per Cent.

△ = Series 19—Tee Pump—Length of Eduction Pipe 41.60 Feet—Average Lift 23.96 Feet—Average Submergence 42.40 Per Cent.

Effect of Diverging Outlet

Fig. 40 shows the effect of increasing the diameter of the eduction pipe at its upper end, thus decreasing the velocity of discharge and conserving part of the kinetic energy of the velocity head. The two series of experiments were performed under similar conditions, with the exception that 7.5 feet of 2-inch pipe and a 2-inch elbow replaced 7.5 feet of 1¼-inch

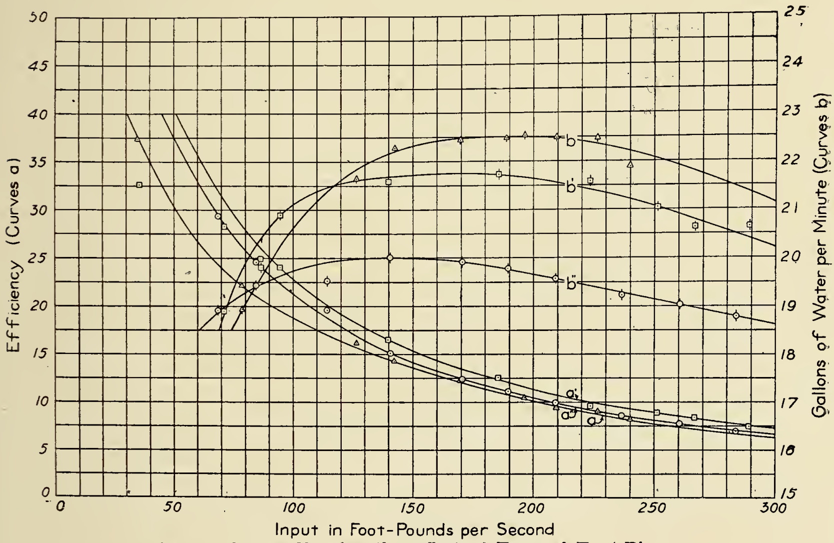


Fig. 39.—Curves Showing the Effect of Type of Foot-Piece.

○ = Series 14—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 41.50 Feet—Average Lift 7.66 Feet—Average Submergence 81.54 Per Cent.
□ = Series 17—1¼-Inch Indiana Foot-Piece—Length of Eduction Pipe 42.08 Feet—Average Lift 7.63 Feet—Average Submergence 81.95 Per Cent.
△ = Series 18—Tee Pump—Length of Eduction Pipe 41.60 Feet—Average Lift 6.58 Feet—Average Submergence 84.18 Per Cent.

pipe and a 1¼-inch elbow at the upper end of the eduction pipe. The enlargement from the 1¼-inch pipe to the 2-inch pipe was made by means of a standard cast-iron reducer. The enlargement of the upper part of the pipe caused a large increase in the discharge and hence in the efficiency. This diagram illustrates forcibly the necessity of keeping the velocity at the outlet as small as possible. Had the experiment been made with a more gradual enlargement, increasing the diam-

eter at the outlet to a larger diameter, still better results would doubtless have been secured.

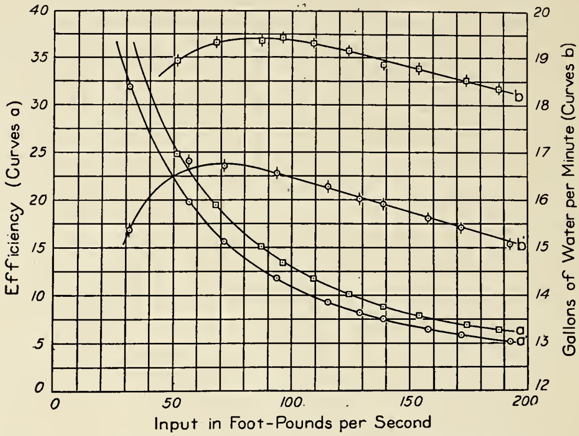


Fig. 40.—Curves Showing the Effect of a Diverging Outlet.

⊙ = Series 11—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 26.74 Feet—Average Lift 4.74 Feet—Average Submergence 82.40 Per Cent.

⊡ = Series 13—1¼-Inch Harris Foot-Piece—Length of Eduction Pipe 26.74 Feet—Average Lift 4.79 Feet—Average Submergence 82.23 Per Cent.—7.5 Feet of 1¼-Inch Pipe at Upper End of Eduction Pipe Replaced by 2-Inch Pipe.

This method of piping the well may be used to advantage when the lower part of the well is of a smaller bore than the upper part.

STUDY OF THE SIZE OF AIR BUBBLES

Reference has been made, on a previous page, to the fact that there is a difference of opinion as to the desirability of having the air in small bubbles in the rising column of water.

Experiments made with small glass tubes generally show the bubbles to be of a practically uniform size and of the form shown in Fig. 3 (b) ; the horizontal cross-sectional area of the bubble being about one-half the area of the pipe bore. Under these conditions the bubbles rise with a uniform motion and with very little disturbance of the intermediate layers of water. The action in a large pipe under operating conditions of velocity, etc., are, however, quite different.

The sixteen feet of glass pipe forming part of the eduction pipe used in the Wisconsin experiments afforded a good opportunity to study the action of the air in a pump of commercial size, under the conditions of the first experiments. The Harris foot-piece used in this series of experiments was designed, as shown in Figs. 11 and 12, to discharge the air, in the form of a thin shell, through an annular slit in the upper end of the nozzle just below the entrance to a contracted tube or sleeve; the evident purpose of the design being to promote such an intimate mixture of the air and water as would result in the production of small bubbles. If such action occurred, its effect was largely lost before the mixture of air and water rose to the beginning of the glass pipe, which was about a foot above the air nozzle.

When the air was admitted to the pump at a very low rate, so that it simply rose through the water without pumping, the bubbles took the form of a single convex lens, with the convex side upward. The under side of the bubbles was a practically level water surface, and the edges of the bubbles were quite sharp. The diameter of the bubble appeared, through the cylindrical glass walls, to be nearly as great as the diameter of the pipe bore. Such bubbles rose through the water with very steady uniform motion. Between such bubbles were occasional

smaller ones, in which the surface tension was great enough to cause them to tend toward an oblate spheroid in form, though their motion was so irregular as to cause them to go through violent contortions.

As the rate of air admission was increased the longitudinal axis of the bubbles was lengthened; the shape of the bubbles becoming ovoid, with the bottom still flat, but the edges no longer sharp. With a further increase in the rate of air admission this general form of bubble persisted until the vertical axis became five or six diameters long. A greater rate of air admission caused a discharge of water which altered the conditions as to actual velocities, pipe friction, etc.

Under the conditions of pumping it was difficult to observe the form of the bubbles precisely on account of the velocity with which they shot through the pipe. Under practically all rates of pumping the bubbles appeared to be quite uniform in length near the foot-piece, being about a foot, or about ten diameters, long. The lower end of the bubble was quite flat, but the upper end appeared to have lost the regularity of form which was so noticeable at slow rates of air admission. The bubbles, in short, appeared as cylindrical pistons of air practically filling the pipe. Between the large air bubbles were pistons of water, of length about equal to that of the air pistons. In the lower part of these pistons of water were numerous small bubbles of air about the size of peas. The upper part of the water piston, which consisted principally of water which had slipped down past the next large air piston above, was clear and free from bubbles.

As the pistons approached the upper end of the glass pipe there were frequent sudden disturbances caused by one of the water pistons losing its equilibrium and slipping bodily down past the air piston below it, thus making two adjacent water and air pistons of double the average length.

Large bubbles, having greater buoyancy per unit area of surface, rise more rapidly through a liquid than do small bubbles. The large bubbles, therefore, overtake the smaller ones and coalesce with them. Likewise eddies in the water cause bubbles to impinge upon one another and coalesce. It appears from the Wisconsin experiments, with the Harris foot-piece,

that the conditions of air admission and flow in the foot-piece were such as to cause most of the bubbles to coalesce within a space of a few pipe diameters above the foot-piece. The conditions of the experiments with the Indiana and Tee foot-pieces did not admit of inspection of the air in rising through the eduction pipe.

Experiments made by Professor E. Josse, in which he used a section of glass pipe in air lift pumps of 79 and 78 mm. diameter respectively, showed the action of the air and water to be exactly similar to that occurring in the somewhat smaller pump used in the present experiments, with the exception that his description* would indicate that there are many more small bubbles in the water pistons which are described as being foam-like. In his experiments the foot-piece was quite similar to our Tee foot-piece, but the air was admitted to the eduction pipe through a narrow annular slit around the pipe wall.

* Prof. E. Josse, Druckluft-Wasserheber, Zeit. des Ver. Deutscher Ingenieure, Band 42, seite 981, Sept. 3, 1898.

RESULTS OF PREVIOUS EXPERIMENTS

While there have been many tests made on actual wells, the facilities for varying the conditions of operation or for making accurate measurements of the quantities have been limited, and knowledge of comparative tests is, therefore, confined chiefly to laboratory tests. Brief outlines of those tests with which the writers have become familiar will be found in the succeeding paragraphs.

Browne and Behr Experiments.—The experiments were performed on a 10-inch well with a depth of 55 feet. The diameter of the eduction pipe used was three inches, with lengths of 51.6, 88.3, and 128.2 feet. The diameter of the air pipe was 1 inch, and a Pohle foot-piece with a nozzle 5/8 inches in diameter was used. The water was measured by means of a weir and the air by volumetric measurement, checked by the flow through an orifice. The efficiency, based on the least work theoretically required to compress the air, so that it did not include the compressor, ranged from 2 to 53 per cent. The conclusions derived from these experiments were:

(1) Efficiency for a given lift and submergence was greatest when the pressure in the receiver did not greatly exceed the head due to submergence.

(2) Efficiency increased with the percentage of submergence.

Josse's Experiments.—Experiments performed at the technical institute at Charlottenburg, Germany. The comparative tests undertaken were: (1) with a lift having a discharge pipe 119.75 feet long and corrugations of 2.76 and 3.07 inches in minimum and maximum diameter, (2) with a lift having a smooth discharge pipe of the same length and 2.76 inches in diameter, and (3) with a lift having a smooth discharge pipe of the same length and 3.07 inches in diameter. Three comparative tests were made under above conditions, differing in the percentage of submergence. The water was measured by volumetric measurement and the amount of air computed from the number of strokes of the air piston and cards taken from the air cylinder, which gave the volumetric efficiency

Computations checked by volumetric measurement and found to be sufficiently accurate. The efficiency was calculated from the indicated work done in the air cylinder and the lift and volume of water raised.

Conclusions: Under similar conditions the smooth pipe gave an efficiency of about 45 per cent., the corrugated pipe about 25.7 per cent. and about half as much water delivered in the case of the corrugated pipe. However, the foot-pieces used with the two types of discharge pipe differed, the smooth pipe having a foot-piece which discharged the air all around the circumference of the pipe, while in the case of the corrugated pipe the air was introduced by a simple U bend at the bottom of the air pipe, with its free end in the center of the discharge pipe. In order to test the influence of this foot-piece, a series of experiments were made using the U bend foot-piece with the smooth discharge pipe. It was found that at high rates of pumping there was practically no difference in the discharge, but that at normal rates the foot-piece discharging the air around the circumference of the pipe discharged about 25 per cent. more water.

A series of runs in which the submergence, lift, type of foot-piece and size of discharge pipe remained constant, showed that by increasing the amount of air the water discharged increased to a certain point and then decreased.

A series of experiments were also made on actual wells from which Professor Josse deduced the following conclusions: (1) If submergence and lift be kept constant, the amount of air per volume of water will not vary much with the size of the pump. (2) With increasing lift the volume of air per volume of water increases, and hence the efficiency decreases. (3) Other things being equal, an increase in the area of the discharge pipe of 20 per cent. only increased the discharge 1.2 per cent.

The efficiencies varied from 20 to 45 per cent. in the laboratory tests, and from 22 to 28 per cent. in operating wells.

Kelly's Experiments.—Experiments performed at Preesall, Lancashire, on actual wells. Water measured by volumetric measurement. Air measured by piston displacement and indicator cards were taken from steam and air cylinders. Effi-

ciencies were calculated from the ratio of the work done in raising the water to the work indicated in the air cylinders of the compressor.

Same general result obtained in regard to efficiency, discharge and ratio of volume of air to volume of water, when one well was working alone or when two or three were working together. One well was piped according to the side inlet system and three wells were piped according to the annular tube system, the air entering the eduction pipes through their open ends. The size of air and eduction pipe varied for the different wells. In the well piped according to the side inlet system, the upper end of eduction pipe was enlarged from 4 to 6 inches in diameter in order to reduce the velocity of discharge. Total length of eduction pipe varied from 433 feet to 323 feet for the different wells. The highest efficiency was about 40 per cent., obtained when three wells were working together.

Conclusions:

(1) Highest efficiency obtained at lowest rate of working.

(2) Discharge increases as the rate of working increases, with a tendency to decrease after the rate of working reaches a certain point.

(3) A percentage of submergence of 60 gave a better efficiency than one of 50, other conditions remaining the same.

(4) A well piped with 5-inch eduction and 7-inch air pipe gave higher efficiencies than one piped with a 4-inch eduction and 6-inch air pipe, other conditions remaining the same.

(5) The well piped with the side inlet system and diverging outlet appeared to give better results than the other wells, the cross sectional area of the eduction pipe remaining equal.

(6) The action of the compressed air in an air lift may be either similar to that of a piston in a cylinder, it may form an emulsion with the water, or it may produce a combination of both, the result depending on the rate of working. The piston like layers were obtained with the higher rates of working.

Darapsky and Schubert Analysis of Experiments.—An analysis of Prof. Josse's and other experiments, performed by the firm of Desenisz and Jacobi, from which the authors deduce an empirical formula for computing the amount of air required

per volume of water pumped, and from which by the aid of a theoretical analysis, they deduce the following conclusions:

(1) The lift and velocity remaining constant the efficiency increases as the percentage of submergence increases.

(2) The lift and percentage of submergence remaining constant the efficiency decreases as the velocity increases.

(3) The submergence and velocity remaining constant the efficiency decreases as the lift increases.

(4) The percentage of submergence and velocity remaining constant the efficiency decreases slightly with the lift.

A few experiments with glass tubes showed that by adding a very short length of pipe to the pump as a tail-piece, the discharge as compared with the discharge without a tail-piece, was first diminished, then increased and again diminished as the length of the tail-piece was increased, the supply of air to the pump remaining constant. In the case of a 1.88-inch pipe the maximum discharge was obtained when the length of the tail-piece was about twelve times the diameter.

Westinghouse Air Brake Co's. Experiments.—An extensive series of tests comprising nearly 1,800 different experiments, covering nearly 400 different combinations of discharge pipe, diameter, lift and submergence, were made by the Westinghouse Air Brake Co. The results and conclusions of the tests have been published, but no numerical data or curves showing the relation of discharge, air consumption, etc., have been given to the public. The experiments were all made on an actual well, 6 inches in diameter and 174 feet deep. The discharge was weighed and amount of air computed by observing the initial and final pressures in a tank of known volume. The following conclusions, taken from an article in the Engineering News of June 18, 1908, indicate what these tests showed.

(1) The rate of delivery of water, and the air consumption per gallon, with fixed size of discharge pipe, are practically constant for all lifts, provided the ratio of lift to submergence is maintained constant.

(2) With a discharge pipe of given diameter, the delivery decreases and the air consumption per gallon increases as the ratio of lift to submergence increases.

(3) With a fixed ratio of lift to submergence, the air consumption per gallon decreases as the size of the discharge pipe increases.

(4) The least air pressure that will give continuous flow is the proper pressure to use. A slightly lower pressure gives intermittent delivery, and the amount delivered is much decreased, though the air consumption per gallon is slightly lower than with continuous flow. With pressure higher than just enough to give continuous flow, the delivery is increased somewhat, but the air consumption per gallon delivered is increased in greater ratio; and with further increase in air pressure a point of maximum delivery is reached, beyond which the delivery is decreased in amount. The sound of the discharge is a reliable guide to proper regulation of the air supply.

(5) It appears from (2) that by increasing the submergence, i. e. locating the foot-piece deeper down in the water, for a given lift, the air consumption is progressively reduced. But as the required air pressure is increased with the greater depth, a cubic foot of air represents greater power. A curve representing the variation of horsepower required per gallon of water delivered, with depth varying, shows that the power first decreases with increasing depth, then reaches a maximum and thence increases. The ratio of lift to submergence at this minimum point may be called the "economical ratio."

(6) For a given size of discharge pipe the economical ratio decreases as the lift increases; i. e. the submergence should be increased in greater ratio than the lift. For a given lift, the economical ratio increases (submergence decreases) as the size of discharge pipe increases.

(7) A tail-piece or projection of the discharge pipe below the air inlet is essential in starting, as it tends to prevent the air from backing down into the well and rising in the casing outside the discharge pipe.

(8) Anything in the shape of a jet or pipe introduced into the discharge pipe to serve as an air inlet has no value, and is, in fact, detrimental by forming an obstacle to the free passage of water.

(9) The size of the air pipe is determined only by consid-

erations of friction loss required to force the air through the pipe.

Duty Tests

The published results of duty tests on air lift plants are few in number. The plant is usually so arranged that a duty test is rather difficult to make, as the compressor takes steam from the same main as the force pumps. In order to give the reader an idea of the performance of an air lift plant figured on a duty basis, the following published tests are herewith appended:

"The plant at Atlantic City, N. J., showed a satisfactory duty ranging roughly from 20,000,000 to 25,000,000 foot pounds work per 1,000 pounds of dry steam. The pumping plant comprised a Rand duplex flywheel compressor, having 10-inch and 16-inch cross compound steam cylinders of 12-inch stroke, 13x12-inch air cylinder, Corliss inlet valves, and poppet discharge valves; a compressor of the same type with 11-inch and 18x14-inch stroke steam end and 16x14-inch air end, having Meyer adjustable valves on the steam cylinders; a Wainwright surface condenser; a Deane combined wet vacuum and circulating pump, with 5½x7-inch steam end and 6x7-inch pumps; an air receiver 28 inches by 8 feet; and galvanized piping to the wells, with valves. The smaller compressor was to be in reserve. The contract price for the pumping equipment complete was $8,250. Plant consisted of 13 wells with a capacity of about 5,450,000 gallons per 24 hours. The average lift is about 27 feet and submergence about 60 per cent."

"A comparison between the efficiency of wells pumped with air lift and steam deep well pumps at Waukesha, Wis., showed an efficiency of between 16 and 18 per cent. for air lift based on I. H. P. in steam cylinder and an efficiency of 74.8 per cent. for deep well pumps based on I. H. P. of engine."

Air Lift.

Duty per 100 pounds of coal...... 8,200,000 foot pounds
Duty per 1,000 pounds of steam...11,940,000 foot pounds

Deep Well Pumps.

Duty per 100 pounds of coal......34,500,000 foot pounds
Duty per 1,000 pounds of steam...53,300,000 foot pounds

In a paper read before the American Water Works Association, Mr. D. W. Mead estimates the duty of an air lift plant for different types of compressors as follows, assuming the efficiency (based on I. H. P. in steam cylinder) of the air lift to vary from 15 to 25 per cent.

Type of Compressor	Steam consumption, pounds dry steam per I. H. P.	Duty, in million foot pounds with	
		15 per cent. efficiency	25 per cent. efficiency
Compound Corliss compressor	16 to 20	19 to 30	31 to 25
Simple condensing Corliss compressor	22 to 28	13 to 10	22.5 to 18
Simple Corliss compressor	35 to 40	9.5 to 8.5	14 to 12
Well designed high pressure compressor	40 to 60	8.5 to 5	12 to 8
Small straight line compressor	50 to 80	6 to 4.5	10 to 6

CONCLUSION

A comparison of the advantages and disadvantages of the air lift pump shows that there is a field of usefulness of sufficient magnitude to make it an important apparatus deserving of further theoretical and experimental study. From a study of the foregoing discussion and accompanying data, ideas in regard to improvement in the design will no doubt be suggested to the designer or experimenter. However, a full realization of the complexity of the action must be appreciated, as also the number of variables which enter into the problem. In order to facilitate the study of results, the variables which may affect a particular type and size of pump are again given at this place. They are (1) percentage of submergence, (2) lift, (3) discharge, (4) volume of air, (5) pressure of air. The conclusions which may justifiably be deduced from the Wisconsin experiments are given below, and hold only for the particular type, size and length of pump on which the experiments were performed. The inference, however, may be drawn that these conclusions would hold for other types and sizes.

(1) The central air tube pump has the greatest theoretical capacity for a given size of well.

(2) The coefficient of pipe friction and slip decreases as the discharge increases, and decreases as the ratio of volume of air to volume of water increases. (See Fig. 20.)

(3) The coefficient of pipe friction and slip varies with the length of pump, but seems to be independent of the percentage of submergence and of the lift.

(4) The length of pump, the percentage of submergence, and therefore, the lift remaining constant, there is a definite quantity of air causing the maximum discharge. This quantity of air for maximum discharge, as also the ratio of volume of air to volume of water, differs for different percentages of submergence and lift, the length of the pump remaining constant. (See. Fig. 21.)

(5) The length of pump remaining constant, the maximum output (e. g. foot gallons) occurs at about the same percent-

age of submergence for all rates of air consumption, being at from 61 to 65 per cent. for the pump used in the Wisconsin experiments. At other submergences the output varies as the ordinates of a parabola having a vertical axis. Under these conditions the lift does not remain constant as the percentage of submergence varies. (See Figs. 23 and 24.)

(6) The length of pump and percentage of submergence remaining constant, and therefore constant lift, the efficiency increases as the input decreases, that is, the highest efficiencies are obtained at the lowest rates of pumping. (See Figs. 27, 28, and 30.)

(7) By varying the percentage of submergence, and therefore the lift, the length of pump remaining constant, the maximum efficiency is obtained at approximately 63 per cent. submergence for all rates of input or discharge. (See Figs. 27, 28, and 29.)

(8) The lift remaining constant, the efficiency increases as the percentage of submergence increases, for all rates of input and all practical percentages of submergence. (See Figs. 30 and 31.)

(9) With the same size and type of pump, the percentage of submergence remaining constant, the efficiency increased as the lift increased for the small lifts experimented on, that is, up to about 24 feet. From a theoretical study, however, the indications are that a point will be reached from which the efficiency will decrease as the lift increases. (See Figs. 32, 33 and 34.)

(10) Other conditions remaining constant, there is no advantage to be gained by introducing compressed air above the surface of the water in the well. (See Figs. 35, 36, and 37.)

(11) The type of the foot-piece has very little effect on the efficiency of the pump, so long as the air is introduced in an efficient manner and the full cross sectional area of the eduction pipe is realized for the passage of the liquid. Anything in the shape of a nozzle to increase the kinetic energy of the air is detrimental. (See Figs. 38 and 39.)

(12) A diverging outlet which will conserve the kinetic energy of the velocity head increases the efficiency. (See Fig. 40.)

TABLE I

Series I

$1\frac{1}{4}$ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a $1\frac{1}{4}$ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
1	.04407	18.007	21.843	.5766	.00923	4.143	43.77	10.865	6.265	28.684	4.775	1.08	.2199
2	.04429	18.061	22.222	.5834	.00933	4.187	44.39	10.743	6.268	28.209	4.747	1.09	.2200
3	.18057	19.104	108.380	.6867	.01098	4.928	43.47	10.923	7.501	6.921	16.446	1.29	
4	.12338	18.445	64.830	.7500	.01200	5.386	43.26	10.963	8.222	12.683	10.282	1.41	.0788
5	.12004	18.480	63.570	.7519	.01203	5.399	43.26	10.962	8.242	12.965	9.979	1.41	.0822
6	.09154	18.231	45.860	.7326	.01172	5.260	42.50	11.110	8.139	17.747	7.811	1.37	.1000
7	.06307	18.213	31.477	.7194	.01151	5.166	44.01	10.817	7.782	24.723	5.480	1.35	.1300
8	.03174	18.182	15.731	.3068	.00491	2.204	44.37	10.748	3.298	20.961	6.465	0.58	.7382
9	.04428	18.388	22.961	.6745	.01079	4.843	48.34	9.982	6.733	29.325	4.104	1.27	.1821
10	.05909	18.609	32.108	.8333	.01333	5.984	47.85	10.076	8.396	26.150	4.433	1.56	.1188
11	.07671	18.554	41.130	.9091	.01454	6.526	47.91	10.064	9.148	22.243	5.276	1.70	.0883
12	.09592	18.657	52.970	.8969	.01435	6.441	48.15	10.018	8.984	16.962	6.685	1.69	.0810
14	.03910	18.501	21.173	.4934	.00789	3.541	47.31	10.180	5.023	23.724	4.956	0.93	.3458
15	.08244	18.664	45.518	.9259	.01481	6.647	49.25	9.806	9.079	19.946	5.567	1.74	.0863
16	.13004	18.846	74.540	.8734	.01397	6.270	48.57	9.936	8.678	11.643	9.308	1.64	.0384
17	.12377	18.642	68.110	.7813	.01250	5.610	47.73	10.098	7.890	11.584	9.901	1.47	.0802
18	.12160	18.574	67.140	.8048	.01288	5.781	45.99	10.435	8.398	12.508	9.441	1.51	.0778
19	.11300	18.552	62.130	.8214	.01314	5.897	45.88	10.456	8.589	13.825	8.600	1.54	.0805
20	.09660	18.581	53.300	.8830	.01413	6.342	47.64	10.116	8.933	16.760	6.837	1.66	.0830
21	.08652	18.480	46.752	.8715	.01394	6.257	47.65	10.114	8.814	18.854	6.207	1.63	.0895
22	.07158	18.451	38.433	.8772	.01403	6.297	47.35	10.172	8.923	23.220	5.102	1.64	.0978
23	.05665	18.511	30.825	.8584	.01373	6.163	47.47	10.150	8.712	28.264	4.126	1.61	.1141

Series I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second,	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
24	.05198	18.414	27.747	.7722	.01235	5.543	48.02	10.042	7.754	27.945	4.209	1.46	.1396
25	.04198	18.588	23.245	.7649	.01224	5.494	47.12	10.216	7.814	33.618	3.430	1.43	.1561
26	.02961	18.628	16.509	.4838	.00774	3.474	47.49	10.146	4.908	29.731	3.826	0.90	.4143
27	.13172	18.306	69.660	.6757	.01081	4.852	41.15	11.370	7.682	11.027	12.185	1.27	.0857
28	.10438	18.019	51.660	.6612	.01059	4.753	41.20	11.360	7.511	14.540	9.857	1.24	.1020
29	.08644	17.917	41.755	.6678	.01068	4.793	41.20	11.360	7.586	18.168	8.094	1.26	.1138
30	.07118	17.840	33.710	.6601	.01056	4.739	41.20	11.360	7.498	22.243	6.741	1.24	.1287
31	.05195	17.845	24.597	.6289	.01006	4.515	41.22	11.356	7.142	29.036	5.164	1.18	.1626
32	.03002	18.075	15.075	.4926	.00788	3.537	41.23	11.354	5.592	37.103	3.810	0.93	.3185
33	.04664	17.954	22.707	.6411	.01026	4.605	41.20	11.360	7.283	32.075	4.546	1.21	.1689
34	.04134	18.032	20.524	.5899	.00944	4.237	41.25	11.350	6.695	32.622	4.379	1.10	.2119
35	.13191	19.009	78.380	.9389	.01502	6.741	49.46	9.765	9.168	11.697	8.782	1.76	.0636
36	.10667	18.411	56.170	.7859	.01257	5.642	49.73	9.712	7.633	13.588	8.486	1.48	.0902
37	.08281	18.505	44.525	.8696	.01391	6.243	48.08	10.030	8.722	19.590	5.953	1.63	.091
38	.06049	18.560	32.893	.8753	.01400	6.283	48.23	10.002	8.754	26.615	4.321	1.64	.107
39	.05265	18.495	28.226	.7663	.01226	5.503	49.12	9.830	7.532	26.686	4.294	1.44	.143
40	.04789	18.628	26.405	0.7519	.01203	5.399	48.96	9.862	7.416	28.087	3.981	1.41	.157
41	.12336	18.502	66.320	0.6359	.01017	4.564	48.41	9.968	6.339	9.559	12.130	1.20	.105
42	.11093	19.155	67.730	1.0498	.01680	7.541	53.58	8.968	9.414	13.899	6.603	1.97	.0[illegible]48
43	.09123	19.068	54.830	1.0811	.01730	7.765	53.29	9.022	9.753	17.789	5.274	2.03	.071
44	.08085	19.098	48.752	1.1237	.01798	8.070	54.40	8.810	9.900	20.307	4.497	2.11	.072

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
45	.07195	19.071	43.245	1.1080	.01773	7.957	54.38	8.814	9.766	22.584	4.058	2.08	.0782
46	.06109	19.070	36.715	1.1049	.01768	7.935	54.72	8.748	9.666	26.327	3.456	2.08	.0831
47	.04831	18.989	28.573	1.0102	.01616	7.253	53.96	8.894	8.984	31.443	2.989	1.90	.1022
48	.03775	18.919	22.055	0.7533	.01205	5.408	53.64	8.950	6.742	30.571	3.133	1.42	.1886
49	.09612	19.193	59.790	1.2658	.02025	9.089	58.06	8.102	10.255	17.152	4.747	2.38	.0557
50	.08354	19.202	52.130	1.2780	.02045	9.178	58.20	8.076	10.321	19.800	4.085	2.41	.0596
51	.08096	19.203	50.510	1.2423	.01988	8.923	58.18	8.080	10.037	19.873	4.073	2.34	.0642
52	.06112	19.206	38.137	1.2384	.01981	8.891	58.43	8.032	9.946	26.083	3.085	2.32	.0723
53	.05291	19.206	33.013	1.1662	.01866	8.375	58.21	8.074	9.415	28.523	2.836	2.19	.0841
54	.04347	19.212	27.158	1.0928	.01748	7.845	57.96	8.122	8.875	32.680	2.487	2.05	.0981
55	.03097	19.213	19.347	0.8429	.01349	6.055	57.84	8.144	6.864	35.479	2.296	1.58	.1727
56	.10173	17.312	56.050	0.5690	.00910	4.084	38.01	11.976	6.815	12.158	11.180	1.07	.1016
57	.09045	17.382	38.823	0.6678	.01068	4.794	39.24	11.738	7.839	20.193	8.469	1.26	.0900
58	.08222	17.378	35.286	0.5031	.00805	3.613	38.76	11.832	5.952	16.868	10.214	0.95	.1526
59	.06988	17.383	29.994	0.4949	.00792	3.555	38.74	11.836	5.857	19.526	8.823	0.93	.1780
60	.06207	17.383	26.641	0.4969	.00795	3.568	38.77	11.830	5.878	22.065	7.808	0.94	.1901
61	.04920	17.384	21.117	0.5025	.00804	3.608	38.82	11.820	5.939	28.127	6.120	0.94	.2113
62	.04412	17.384	18.937	0.4587	.00734	3.294	38.87	11.810	5.417	28.605	6.011	0.86	.2598
63	.05371	17.384	23.053	0.4926	.00788	3.537	38.93	11.798	5.812	25.212	6.816	0.93	.2137
64	.04413	17.384	20.065	0.4926	.00788	3.537	39.00	11.786	5.806	28.937	5.601	2.93	.2778
65	.07917	19.844	55.450	1.4286	.02286	10.260	63.77	7.000	10.000	18.035	3.463	2.69	.0613

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water' in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w	q_w	q_g	s	h_1	l_o	e	$\frac{q_a}{q_w}$	v_1	c_p
66	.07067	19.592	47.600	1.4494	.02319	10.408	63.67	7.022	10.177	21.380	3.048	2.72	.0586
67	.11658	20.108	84.090	1.4337	.02294	10.296	63.78	6.997	10.032	11.930	5.082	2.69	.0498
68	.09816	19.964	69.200	1.4337	.02294	10.296	63.68	7.017	10.060	14.537	4.279	2.69	.0545
69	.09712	19.905	67.940	1.4388	.02304	10.341	63.06	7.136	10.266	15.113	4.215	2.70	.0536
70	.09265	19.823	64.000	1.4236	.02278	10.224	64.80	6.800	9.680	15.126	4.067	2.68	.0558
71	.08114	19.771	55.590	1.4184	.02269	10.184	64.82	6.798	9.642	17.345	3.576	2.66	.0601
72	.08055	19.764	55.180	1.4337	.02294	10.296	62.12	7.318	10.491	19.013	3.511	2.69	.0576
73	.07391	19.742	50.410	1.4286	.02286	10.260	62.72	7.202	10.288	20.410	3.233	2.69	.0602
74	.06245	19.677	42.118	1.4235	.02278	10.224	62.55	7.235	10.299	24.453	2.742	2.68	.0625
75	.05394	19.702	36.580	1.4036	.02246	10.081	62.48	7.250	10.176	27.820	2.402	2.64	.0662
76	.03148	19.790	21.626	No	water		64.85	6.792		pumpe	d		
77	.12212	20.165	87.870	1.4134	.02261	10.148	63.55	7.043	9.954	11.330	5.401	2.65	.0489
78	.10305	20.056	72.950	1.4036	.02246	10.081	63.65	7.023	9.857	13.537	4.588	2.64	.0550
79	.08105	19.838	55.520	1.4286	.02286	10.260	63.80	6.995	9.993	18.000	3.546	2.69	.0586
80	.09444	20.373	69.960	1.4235	.02278	10.224	63.84	6.988	9.947	14.218	4.146	2.68	.0611
81	.07146	19.837	48.947	1.4084	.02253	10.112	63.88	6.978	9.827	20.077	3.172	2.64	.0639
82	.06102	19.783	41.427	1.4494	.02319	10.408	63.93	6.970	10.103	24.387	2.631	2.72	.0621
83	.05726	19.781	38.878	1.4286	.02286	10.260	63.94	6.968	9.954	25.604	2.505	2.69	.0646
84	.04501	19.783	30.559	1.3888	.02222	9.973	63.99	6.958	9.663	31.620	2.026	2.61	.0694
85	.02858	19.849	19.633	1.2196	.01951	8.757	63.90	6.975	8.507	43.333	1.465	2.29	.0848
86	.03994	19.827	27.360	1.3559	.02169	9.735	63.86	6.983	9.468	34.606	1.842	2.55	.0731

Series I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
87	.12640	20.499	97.310	1.5564	.02490	11.175	68.30	6.125	9.533	9.797	5.077	2.92	.0450
88	.11485	20.354	86.570	1.5504	.02481	11.135	68.08	6.168	9.563	11.046	4.629	2.91	.0477
89	.10194	20.284	76.210	1.5444	.02471	11.090	68.00	6.183	9.549	12.530	4.126	2.90	.0517
90	.06883	20.236	51.100	1.6001	.02560	11.490	67.88	6.205	9.928	19.429	2.689	3.01	.0581
91	.08070	20.184	59.440	1.6065	.02570	11.534	68.21	6.142	9.866	16.597	3.140	3.02	.0536
92	.07168	20.046	51.840	1.5936	.02550	11.445	68.22	6.140	9.784	18.874	2.811	2.99	.0555
93	.14772	21.011	120.840	1.5936	.02550	11.445	70.30	5.738	9.144	7.567	5.793	2.99	....
94	.10643	20.678	83.390	1.5936	.02550	11.445	68.06	6.172	9.835	11.793	4.174	2.99	.0508
95	.09305	20.517	71.350	1.6130	.02581	11.584	67.94	6.195	9.992	14.005	3.606	3.03	.0524
96	.07808	20.351	58.560	1.6265	.02602	11.678	67.44	6.290	10.230	17.470	3.001	3.05	.0540
97	.07172	20.368	53.890	1.7167	.02747	12.328	71.20	5.566	9.554	17.729	2.612	3.23	.0515
98	.07137	20.264	52.820	1.5747	.02519	11.306	70.16	5.765	9.077	17.185	2.833	2.96	.0602
99	.06761	20.386	50.970	1.6461	.02634	11.822	68.23	6.138	10.104	19.825	2.567	3.09	.0563
100	.05948	20.273	44.108	1.6461	.02634	11.822	68.70	6.048	9.955	22.570	2.258	3.09	.0566
101	.05053	20.252	37.372	1.5936	.02550	11.445	68.87	6.015	9.585	25.648	1.982	2.99	.0618
102	.03959	20.252	29.282	1.5094	.02415	10.838	69.26	5.940	8.965	30.617	1.639	2.84	.0695
103	.02760	20.230	20.360	1.1155	.01785	8.011	69.10	5.970	6.659	32.707	1.546	2.10	.1360
104	.00707	20.620	5.425	No	water		85.71	2.751		pumped			
105	.00221	20.356	1.634	"	"		69.56	5.882		"			
106	.02240	15.217	2.823	"	"		24.87	14.514		"			
107	.02240	16.134	5.551	"	"		25.40	14.412		"			

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubis feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_o	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
108	.01307	17.106	4.848	No	water		31.18	13.296		pumped			
109	.00697	17.934	3.284	"	"		41.54	11.294		"			
110	.00216	20.350	1.595	"	"		70.30	5.738		"			
111	.00857	17.501	3.600	"	"		41.03	11.394		"			
112	.00428	19.178	2.621	"	"		51.45	9.380		"			
113	.00426	19.120	2.585	"	"		58.25	8.064		"			
114	.00679	18.478	3.628	"	"		46.37	10.362		"			
115	.00212	19.455	1.363	"	"		62.00	7.342		"			
116	.10044	20.930	81.390	1.8348	.02935	13.173	74.90	4.850	8.898	10.933	3.422	3.45	.04[illegible]
117	.10294	20.920	83.330	1.8264	.02922	13.114	75.00	4.830	8.821	10.585	3.523	3.43	.04[illegible]
118	.09423	20.852	75.570	1.8518	.02962	13.294	74.92	4.846	8.973	11.875	3.181	3.48	.04[illegible]
119	.08458	20.814	67.510	1.8692	.02991	13.424	74.88	4.852	9.069	13.433	2.828	3.52	.04[illegible]
120	.07523	20.794	59.930	1.8780	.03005	13.487	74.91	4.848	9.104	15.192	2.504	3.54	.04[illegible]
121	.06751	20.776	53.670	1.8780	.03005	13.487	74.88	4.852	9.112	16.978	2.247	3.54	.04[illegible]
122	.05883	20.677	46.145	1.8868	.03019	13.550	74.77	4.874	9.196	19.928	1.949	3.55	.04[illegible]
123	.04866	20.679	38.203	1.8517	.02962	13.294	74.84	4.860	8.999	23.558	1.643	3.48	.0[illegible]
124	.03660	20.677	28.708	1.7544	.02807	12.598	75.15	4.800	8.421	29.335	1.304	3.30	.0[illegible]
125	.04616	20.584	35.817	1.8100	.02896	12.997	74.66	4.894	8.857	24.727	1.594	3.41	.0[illegible]
126	.02924	20.580	29.666	1.5152	.02424	10.879	75.13	4.804	7.279	24.535	1.20[illegible]	2.84	.0[illegible]
127	.05779	20.588	44.885	1.8517	.02962	13.294	74.59	4.910	9.092	20.256	1.951	3.48	.0[illegible]
128	.06459	20.643	50.460	1.8692	.02991	13.424	74.50	4.926	9.208	18.250	2.100	3.52	.0[illegible]

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water id a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	Y_i	c_p
129	.08207	20.718	64.750	1.8692	.02991	13.424	74.54	4.918	9.193	14.197	2.744	3.52	.0452
130	.01955	20.680	15.365	No	water		75.15	4.800		pumpe	d		
131	.11572	20.746	91.560	1.9513	.03122	14.013	79.93	3.878	7.567	8.264	3.707	3.67	.0350
132	.10184	20.753	80.660	1.9902	.03184	14.292	80.00	3.864	7.690	9.534	3.199	3.74	.0369
133	.09086	20.764	72.030	2.0409	.03265	14.654	80.14	3.836	7.828	10.868	2.783	3.84	.0374
134	.14397	21.580	123.820	1.9325	.03092	13.877	80.55	3.758	7.262	5.865	4.657	3.63	......
135	.13171	21.575	113.170	1.9418	.03107	13.944	79.84	3.896	7.565	6.685	4.240	3.66	.0360
136	.10076	21.400	84.870	2.0000	.03200	14.362	79.55	3.950	7.900	9.308	3.149	3.76	.0401
137	.08777	21.000	70.450	2.0305	.03248	14.577	79.55	3.950	8.020	11.383	2.702	3.82	.0391
138	.08420	21.248	69.640	2.0513	.03282	14.730	79.45	3.970	8.143	11.693	2.566	3.85	.0409
139	.07495	21.196	61.650	2.0513	.03282	14.730	79.52	3.958	8.119	13.170	2.284	3.85	.0424
140	.07439	21.193	61.140	2.0620	.03299	14.806	79.52	3.958	8.161	13.348	2.255	3.88	.0420
141	.06756	21.188	55.470	2.0833	.03333	14.958	79.54	3.954	8.237	14.850	2.027	3.91	.0422
142	.06330	21.184	51.970	2.0726	.03316	14.883	79.78	3.908	8.099	15.583	1.909	3.90	.0[illegible]33
143	.05553	21.162	45.421	2.0833	.03333	14.958	79.72	3.918	8.162	17.970	1.666	3.91	.0435
144	.05171	21.067	42.335	1.9763	.03162	14.192	78.93	4.070	8.043	19.000	1.635	3.71	.0491
145	.04637	21.071	38.000	1.9481	.03117	13.989	79.11	4.034	7.858	20.681	1.488	3.67	.0510
146	.04024	21.004	32.670	1.8127	.02900	13.016	78.22	4.208	7.627	23.347	1.388	3.41	.0537
147	.02275	21.003	18.470	1.6667	.02668	11.974	79.19	4.020	6.700	36.276	0.853	3.14	.0589
148	.00708	21.034	5.769	No	water		79.06	4.046		pumpe	d		
149	.14084	21.899	126.830	2.0000	.03200	14.363	84.10	3.072	6.144	4.845	4.402	3.70	......

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
150	.13687	21.874	123.020	2.0135	.03221	14.456	84.27	3.040	6.121	4.976	4.250	3.78	.0355
151	.12498	21.853	111.860	2.0340	.03254	14.605	83.95	3.100	6.305	5.637	3.841	3.82	.0375
152	.11500	21.781	102.330	2.0691	.03310	14.856	83.90	3.110	6.435	6.288	3.474	3.89	.0382
153	.10738	21.749	95.130	2.1127	.03380	15.170	84.50	2.994	6.325	6.649	3.177	3.97	.0384
154	.10107	21.528	88.600	2.1277	.03403	15.228	84.28	3.038	6.464	7.296	2.970	3.99	.0386
155	.09155	21.483	79.850	2.1584	.03453	15.497	84.18	3.056	6.596	8.261	2.651	4.05	.0393
156	.08325	21.466	72.540	2.1819	.03491	15.667	84.44	3.006	6.558	9.041	2.385	4.10	.0403
157	.08042	21.436	69.770	2.2060	.03529	15.838	84.39	3.014	6.649	9.530	2.279	4.15	.0397
158	.07755	21.414	67.110	2.2142	.03542	15.897	84.33	3.028	6.704	9.989	2.189	4.16	.0398
159	.07085	21.385	61.090	2.2223	.03556	15.960	84.28	3.038	6.751	11.053	1.992	4.18	.0404
160	.06289	21.375	54.170	2.2389	.03582	16.077	84.47	3.000	6.716	12.397	1.756	4.21	.0411
161	.05470	21.353	46.913	2.2223	.03556	15.960	84.56	2.984	6.631	14.135	1.538	4.18	.0424
162	.05888	21.353	50.500	2.2223	.03556	15.960	84.40	3.014	6.698	13.264	1.656	4.18	.0420
163	.04977	21.328	42.610	2.1740	.03478	15.610	84.43	3.008	6.539	15.346	1.431	4.08	.0462
164	.03899	21.315	33.320	2.1054	.03368	15.116	84.44	3.006	6.329	18.995	1.158	3.96	.0477
165	.03178	21.322	27.187	1.7753	.02840	12.746	84.37	3.020	5.361	19.720	1.119	3.34	.0716
166	.00215	21.535	1.885	No	water		85.04	2.890		pumped			
167	.14682	22.350	140.500	2.1899	.03503	15.722	90.29	1.876	4.108	2.924	4.192	4.11	......
168	.11795	22.135	110.440	2.3077	.03692	16.570	90.21	1.892	4.366	3.953	3.195	4.33	.0336
169	.13497	22.305	128.640	2.2815	.03650	16.382	91.02	1.736	3.961	3.079	3.698	4.28	.0317
170	.13884	22.324	132.440	2.2389	.03582	16.077	90.31	1.872	4.191	3.165	3.876	4.21	.0322

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1⅛ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_i	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
171	12436	22.172	116.740	2.2729	.03636	16.319	90.06	1.920	4.364	3.738	3.421	4.27	.0334
172	.11134	22.078	103.670	2.3167	.03706	16.633	90.10	1.912	4.429	4.273	3.004	4.35	.0344
173	.10229	22.019	94.450	2.3623	.03780	16.965	90.09	1.916	4.526	4.792	2.706	4.44	.0346
174	.09712	21.975	89.450	2.3810	.03809	17.095	89.96	1.940	4.619	5.164	2.550	4.47	.0348
175	.08709	21.918	79.540	2.4097	.03855	17.302	89.78	1.974	4.757	5.980	2.259	4.53	....
176	.07804	21.886	71.170	2.4491	.03918	17.584	89.78	1.974	4.835	6.793	1.992	4.60	....
177	.07448	21.872	67.870	2.4692	.03951	17.733	89.86	1.960	4.840	7.130	1.885	4.64	....
178	.06739	21.856	61.200	2.4692	.03951	17.733	89.80	1.970	4.864	7.948	1.706	4.64	....
179	.06334	21.859	57.850	2.4794	.03967	17.805	90.34	1.868	4.631	8.006	1.597	4.66	....
180	.05520	21.837	50.340	2.4592	.03935	17.661	90.32	1.870	4.599	9.135	1.403	4.63	....
181	.05963	21.840	54.380	2.4692	.03951	17.733	90.43	1.850	4.568	8.400	1.509	4.64	....
182	.04527	21.831	41.215	2.4195	.03871	17.373	90.32	1.870	4.524	10.977	1.170	4.54	....
183	.03220	21.823	29.290	2.1353	.03416	15.332	89.72	1.986	4.241	14.478	0.943	4.02	.0536
184	.03905	21.753	35.252	2.2814	.03650	16.382	88.99	2.126	4.850	13.759	1.070	4.28	.0454
185	.00218	21.774	1.971	No	water		89.67	1.996		pumpe	d		
186	.13092	22.648	129.490	2.4002	.03840	17.234	95.63	0.844	2.026	1.564	3.410	4.51	....
187	.12525	22.595	123.300	2.4194	.03871	17.373	95.65	0.840	2.032	1.648	3.236	4.55	....
188	.11753	22.529	114.900	2.4491	.03918	17.584	95.55	0.860	2.106	1.833	3.000	4.60	....
189	.10805	22.458	104.960	2.4897	.03983	17.876	95.47	0.874	2.176	2.073	2.713	4.67	....
190	.10038	22.385	96.900	2.5106	.04017	18.028	95.44	0.880	2.209	2.280	2.499	4.72	....
191	.09302	22.333	89.300	2.5533	.04085	18.334	95.37	0.894	2.283	2.556	2.277	4.80	....

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
192	.09000	22.377	86.810	2.5643	.04103	18.414	95.60	0.850	2.180	2.511	2.194	4.82	....
193	.08445	22.327	80.940	2.5974	.04156	18.653	95.48	0.872	2.265	2.798	2.032	4.89	....
194	.07875	22.306	75.360	2.6549	.04248	19.066	95.47	0.874	2.320	3.079	1.854	4.98	....
195	.07531	22.283	71.900	2.6202	.04192	18.814	95.39	0.890	2.332	3.244	1.796	4.92	....
196	.06806	22.255	64.770	2.6433	.04229	18.982	95.38	0.892	2.358	3.641	1.609	4.97	....
197	.06359	22.230	60.420	2.6549	.04248	19.066	95.44	0.880	2.336	3.867	1.497	4.98	....
198	.05979	22.213	56.720	2.6667	.04266	19.147	95.30	0.908	2.421	4.269	1.402	5.01	....
199	.05071	22.203	48.020	2.6667	.04266	19.147	95.34	0.900	2.400	4.998	1.189	5.01	....
200	.04565	22.187	43.200	2.6549	.04248	19.066	95.42	0.884	2.347	5.433	1.075	4.98	....
201	.03973	22.185	37.597	2.6088	.04174	18.733	95.50	0.870	2.270	6.036	0.952	4.90	....
202	.02253	22.210	21.353	2.4794	.03967	17.805	95.96	0.780	1.934	9.057	0.568	4.66	....
203	.00221	22.284	21.114	No	water		94.36	1.090		pumpe	d		
204	.12955	23.034	132.370	2.5237	.04038	18.123	100.29	—0.054	....	....	3.209	4.74	....
205	.12427	23.007	126.890	2.5237	.04038	18.123	100.35	—0.068	....	....	3.078	4.74	....
206	.11348	22.954	115.090	2.5642	.04103	18.415	100.23	—0.046	....	....	2.766	4.81	....
207	.10414	22.833	104.580	2.6060	.04161	18.674	100.02	—0.002	....	....	2.503	4.89	....
208	.10875	22.832	109.230	2.5974	.04156	18.652	100.02	—0.002	....	....	2.617	4.89	....
209	.09923	22.821	99.520	2.6231	.04197	18.837	99.96	+0.006	0.016	0.000	2.364	4.93	....
210	.08862	22.779	88.600	2.6846	.04295	19.277	99.70	+0.058	0.156	0.002	2.063	5.04	....
211	.09365	22.781	93.700	2.6490	.04238	19.021	99.74	+0.050	0.133	0.001	2.210	4.97	....
212	.08556	22.773	85.480	2.7027	.04324	19.406	99.69	+0.060	0.162	0.002	1.979	5.08	....

Series I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift in feet.	Output in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	c_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
213	.08246	22.733	75.770	2.7211	.04354	19.542	99.62	+0.072	0.196	0.003	1.894	5.11	......
214	.07269	22.709	66.680	2.7492	.04399	19.743	99.54	+0.088	0.242	0.004	1.652	5.16	....
215	.06837	22.679	67.780	2.7683	.04429	19.878	99.50	+0.096	0.266	0.004	1.544	5.20	....
216	.06458	22.669	63.970	2.7779	.04444	19.945	99.48	+0.100	0.278	0.004	1.453	5.22	......
217	.06021	22.657	59.460	2.8270	.04523	20.300	99.95	+0.010	0.028	0.000	1.331	5.31	......
218	.05598	22.654	55.280	2.8270	.04523	20.300	99.99	+0.002	0.006	0.000	1.238	5.31	......
219	.03971	22.633	39.155	2.8270	.04523	20.300	99.95	+0.010	0.028	0.001	0.878	5.31	......
219½	.04560	22.203	43.115	2.8471	.04555	20.443	100.03	—0.006	....	....	1.001	5.35	......
220	.03271	22.191	30.905	2.7875	.04460	20.017	100.31	—0.060	....	....	0.733	5.24	....
221	.02280	22.178	21.525	2.5642	.04103	18.414	99.96	+0.008	0.021	0.001	0.556	4.81	....
222	.12788	23.403	135.060	2.6471	.04235	19.007	105.21	—1.008	....	....	3.020	4.97	......
223	.12374	22.377	130.420	2.6666	.04266	19.147	105.11	—0.988	....	....	2.901	5.01	....
224	.11073	23.309	116.030	2.7493	.04399	19.743	105.25	—1.014	....	....	2.517	5.16	....
225	.10584	23.257	110.340	2.7682	.04429	19.878	105.17	—1.000	....	....	2.390	5.20	....
226	.10312	23.234	107.270	2.7778	.04444	19.945	105.06	—0.978	....	....	2.320	5.22	....
227	.10031	23.216	104.270	2.7973	.04475	20.084	105.07	—0.980	....	....	2.242	5.25	....
228	.09511	23.188	95.010	2.8070	.04491	20.157	105.06	—0.978	....	....	2.118	5.27	....
229	.07579	23.148	78.320	2.8470	.04555	20.443	104.95	—0.958	....	....	1.664	5.35	....
230	.08397	23.121	86.490	2.8778	.04604	20.664	104.92	—0.950	....	....	1.824	5.41	....
231	.08059	23.087	82.780	2.9199	.04671	20.964	105.05	—0.974	....	....	1.725	5.48	....
232	.07440	23.070	76.380	2.9521	.04723	21.198	105.09	—0.982	....	....	1.575	5.54	....

SERIES I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
233	.06761	23.044	69.250	2.9963	.04794	21.517	105.17	—1.000	....	....	1.410	5.62	....
234	.06339	22.992	64.630	3.0304	.04849	21.763	105.00	—0.984	....	....	1.307	5.69	....
235	.05810	22.929	58.620	3.0653	.04904	22.010	105.42	—1.048	....	....	1.185	5.75	....
236	.05008	22.927	50.520	3.0890	.04942	22.180	105.30	—1.024	....	....	1.013	5.78	....
237	.04558	22.923	45.950	3.0890	.04942	22.180	105.33	—1.030	....	....	0.922	5.78	....
238	.04068	22.921	41.010	3.0890	.04942	22.180	105.31	—1.026	....	....	0.823	5.78	....
239	.03528	22.919	35.540	3.0304	.04849	21.763	105.26	—1.016	....	....	0.728	5.69	....
240	.01998	22.920	20.128	2.9413	.04706	21.121	105.47	—1.058	....	....	0.425	5.52	....
241	No	air		1.5504	.02481	11.135	105.19	—1.002		used		2.91	....
242	.13492	23.512	143.150	2.8125	.04500	20.196	111.07	—2.140	....	....	2.998	5.28	....
243	.14263	23.523	151.430	2.7610	.04417	19.824	111.17	—2.160	....	....	3.229	5.18	....
244	.12553	23.861	136.980	2.8572	.04572	20.520	110.95	—2.116	....	....	2.746	5.37	....
245	.12973	23.891	141.970	2.8214	.04514	20.260	110.84	—2.096	....	....	2.874	5.30	....
246	.11867	23.801	128.960	2.8847	.04615	20.713	110.69	—2.064	....	....	2.572	5.42	....
247	.11115	23.738	120 200	2.9127	.04662	20.923	110.57	—2.042	....	....	2.384	5.47	....
248	.10592	23.684	113.970	2.9317	.04691	21.054	110.39	—2.008	....	....	2.258	5.51	....
249	.09823	23.638	105.170	2.9803	.04769	21.404	110.35	—2.000	....	....	2.060	5.60	....
250	.08954	23.521	95.130	3.0000	.04800	21.543	109.56	—1.848	....	....	1.866	5.63	....
251	.08043	23.519	85.390	3.1142	.04983	22.364	110.53	—1.996	....	....	1.164	5.85	....
252	.07665	23.489	81.190	3.1579	.05052	22.674	110.14	—1.960	....	....	1.517	5.93	....
253	.07263	23.451	76.660	3.1690	.05070	22.754	110.14	—1.960	....	....	1.433	5.95	....

Series I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
254	.06489	23.434	68.440	3.2143	.05143	23.081	110.01	—1.934	....	....	1.262	6.04	....
255	.06090	23.414	64.050	3.2493	.05199	23.333	110.33	—1.996	....	....	1.171	6.10	....
256	.05619	23.390	59.050	3.2729	.05233	23.486	109.71	—1.878	....	....	1.074	6.14	....
257	.04621	23.382	48.530	3.2848	.05255	23.585	109.96	—1.924	....	....	0.879	6.17	....
258	.03994	23.374	41.911	3.2969	.05275	23.675	110.6[illegible]	—2.048	....	....	0.757	6.19	....
259	.03288	23.390	34.555	3.2493	.05199	23.333	110.96	—2.116	....	....	0.633	6.10	....
260	.02289	23.412	23.902	3.1036	.04965	22.284	110.57	—2.042	....	....	0.461	5.83	....
261	No	air		2.0980	.03357	15.066	109.80	—1.892		used		3.94	....
262	.12304	24.287	137.660	3.0213	.04834	21.695	116.03	—3.098	....	....	2.545	5.67	....
263	.13075	24.364	147.180	2.9852	.04776	21.435	115.97	—3.086	....	....	2.738	5.61	....
264	.11404	24.235	127.070	3.0677	.04908	22.027	115.81	—3.056	....	....	2.324	5.76	....
265	.10711	24.224	119.200	3.1057	.04969	22.303	115.85	—3.064	....	....	2.156	5.83	....
266	.09998	24.161	110.740	3.1447	.05031	22.580	115.76	—3.026	....	....	1.987	....	....
267	.10022	24.110	110.520	3.1849	.05096	22.872	115.47	—2.990	....	....	1.967	5.98	....
268	.08880	24.024	97.180	3.2260	.05162	23.167	115.33	—2.962	....	....	1.720	6.06	....
269	.07680	24.050	84.340	3.3115	.05298	23.778	116.25	—3.140	....	....	1.450	6.22	....
270	.07653	24.040	83.970	3.3333	.05333	23.935	116.06	—3.102	....	....	1.435	6.26	....
271	.06921	24.022	75.750	3.3785	.05406	24.263	115.77	—3.048	....	....	1.280	6.35	....
272	.06533	24.019	71.500	3.4485	.05517	24.762	115.94	—3.080	....	....	1.184	6.48	....
273	.06115	23.968	66.680	3.4604	.05537	24.851	115.65	—3.024	....	....	1.104	6.50	....
274	.05670	23.958	61.800	3.4845	.05575	25.022	115.61	—3.018	....	....	1.017	6.54	....

Series I—Continued

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per spuare inch.	Input, in foot pounds per second.	Dischafge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
275	.04641	23.922	50.400	3.5090	.05614	25.197	115.43	—2.982	....	....	0.827	6.59	....
276	.04044	23.902	43.855	3.5213	.05634	25.286	115.47	—2.990	....	....	0.718	6.61	....
277	.03309	23.881	35.840	3.5590	.05694	25.555	115.33	—2.960	....	....	0.581	6.68	....
278	No	air		2.7550	.04408	19.783	115.82	—3.057		used		5.17	
306	.12283	17.824	57.130	0.4672	.00762	3.420	35.75	12.413	5.911	10.347	16.220	0.89	.1243
307	.12272	17.833	57.360	0.4793	.00767	3.442	35.86	12.392	5.939	10.354	15.600	0.90	.1241
308	.11278	17.745	51.420	0.4793	.00767	3.442	35.14	12.532	6.006	11.680	14.705	0.90	.1319
309	.09949	17.617	43.995	0.4785	.00766	3.438	35.09	12.540	6.000	13.637	12.900	0.89	.1430
310	.08357	17.592	36.955	0.4793	.00767	3.442	35.04	12.550	6.015	16.277	10.897	0.90	.1683
311	.09033	17.595	39.943	0.4800	.00768	3.447	34.81	12.595	6.045	15.135	11.763	0.90	.1567
312	.07275	17.579	32.112	0.4870	.00779	3.496	35.28	12.507	6.092	18.972	9.339	0.91	.1920
313	.06595	17.553	28.860	0.4796	.00767	3.442	35.20	12.520	6.004	20.804	8.599	0.90	.1968
314	.05679	17.514	24.628	0.4598	.00736	3.303	35.22	12.515	5.754	23.363	7.716	0.87	.2267
315	.05016	17.494	21.605	0.4396	.00703	3.155	35.44	12.473	5.484	25.382	7.135	0.82	.2593
316	.04648	17.608	20.695	0.4255	.00681	3.056	35.74	12.415	5.283	25.530	6.825	0.80	.2981
317	.03816	17.607	16.992	0.3643	.00583	2.617	35.87	12.390	4.514	26.562	6.545	0.68	.4215
318	.03290	17.601	20.442	0.2725	.00436	1.957	35.92	12.380	3.374	16.504	7.546	0.51	....

SERIES 2

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input in foot pounds per second.	Discharge of water in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
319	.06355	17.457	26.938	0.3239	.00518	2.325	30.00	13.524	4.381	16.261	12.268	....	....
320	.05166	21.501	44.700	2.1391	.03422	15.356	83.10	3.265	6.984	15.622	1.510	....	....
321	.07371	21.849	66.320	2.1506	.03441	15.445	83.45	3.198	6.878	10.370	2.142	....	....
322	.09043	22.143	83.910	2.1040	.03366	15.108	83.30	3.226	6.787	8.088	2.677	....	....
323	.11443	22.762	112.790	2.0202	.03232	14.506	83.50	3.188	6.441	5.711	3.541	....	....
324	.15172	23.735	162.980	1.8958	.03033	13.613	83.64	3.162	5.995	3.678	5.002	....	....
325	.04865	21.513	42.093	2.1740	.03478	15.612	83.50	3.188	6.931	16.466	1.399	....	....
326	.05167	21.578	45.090	2.1666	.03466	15.558	83.50	3.188	6.907	15.318	1.490	....	....

SERIES 3

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

Average lift 3.44 feet

Average Submergence 82.19 per cent

Supply of Compressed Air in Well Casing Connected with Air Main

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ inch tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
327	.05765	21.471	49.705	2.1052	.03368	15.118	81.73	3.530	7.431	14.950	1.712	....	....
328	.05768	21.483	49.772	2.1097	.03375	15.149	81.76	3.524	7.434	14.937	1.709	....	....
329	.06303	21.612	55.230	2.1391	.03422	15.360	82.48	3.385	7.241	13.411	1.842	....	......
330	.10627	21.936	96.470	2.0774	.03324	14.921	82.55	3.372	7.004	7.261	3.197	....	....
331	.06635	21.712	58.835	2.1220	.03395	15.238	82.55	3.372	7.155	12.161	1.954	....	....

SERIES 4

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

Average Lift 3.29 feet

Average Submergence 82.97 per cent

Supply of Compressed Air in Well Casing Shut off from Air Main

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Ontput, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
332	.02726	21.257	23.127	1.7898	.02864	12.855	83.64	3.162	5.659	24.468	0.952	....	....
333	.02727	21.251	23.115	1.9523	.03123	14.017	83.16	3.254	6.353	27.485	0.873	....	....
334	.04258	21.281	36.257	2.0810	.03329	14.943	82.54	3.375	7.023	19.372	1.279	....	....
335	.05678	21.452	49.327	2.1202	.03392	15.226	82.54	3.375	7.156	14.506	1.674	....	....
336	.07903	21.788	71.280	2.0777	.03324	14.920	82.54	3.375	7.012	9.837	2.378	....	....
337	.09331	21.971	85.790	2.0479	.03276	14.704	82.54	3.375	6.912	8.056	2.848	....	....
338	.11108	22.330	106.020	2.0135	.03221	14.458	82.54	3.375	6.795	6.409	3.449	....	....
339	.12428	22.684	122.530	1.9738	.03158	14.174	83.02	3.286	6.486	5.293	3.936	....	....
340	.14421	23.202	149.000	1.9200	.03072	13.788	83.36	3.215	6.173	4.143	4.694	....	....
341	.16332	23.703	176.120	1.8673	.02987	13.407	83.36	3.215	6.004	3.409	5.465	....	....
342	.02706	21.251	22.937	1.9503	.03120	14.003	83.36	3.215	6.270	27.336	0.867	....	....

Series 5

1¼ inch Annular Air Tube System

Length of Eduction Pipe 19.32 feet

Average Lift 3.02 feet

Average Submergence 84.37 per cent

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds qer second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
343	.03372	22.130	31.545	0.2956	.00473	2.123	83.70	3.149	0.931	2.951	7.129	......	......
344	.05340	22.294	50.940	0.4434	.00709	3.182	85.54	2.794	1.239	2.432	7.532	......	......
345	.08921	22.418	86.120	0.7380	.01181	5.300	86.00	2.705	1.996	2.318	7.554	......	......
346	.11202	22.542	109.380	0.8776	.01404	6.301	84.47	3.001	2.634	2.408	7.978	......	......
347	.12910	22.559	126.280	0.9404	.01504	6.750	84.73	2.950	2.774	2.197	8.584	......	......
348	.15505	22.707	153.930	1.0808	.01729	7.760	84.10	3.072	3.321	2.158	8.968	......	......
349	.02775	21.988	25.663	0.2430	.00389	1.746	85.07	2.885	0.701	2.732	7.134	......	......
350	.04712	22.105	44.045	0.3658	.00585	2.626	86.16	2.675	0.978	2.222	8.055	......	......
351	.07736	22.300	73.850	0.6236	.00998	4.479	86.36	2.636	1.644	2.226	7.751	......	......
352	.07427	22.166	70.760	0.5484	.00877	3.936	85.28	2.844	1.560	2.204	8.469	......	......
353	.11310	22.307	109.220	0.8128	.01300	5.835	84.27	3.040	2.471	2.262	8.700	......	......
354	.13194	22.360	128.130	0.8865	.01418	6.364	82.48	3.385	3.001	2.343	9.304	......	......
355	.16106	22.401	156.890	1.0688	.01710	7.675	80.19	3.828	4.091	2.609	9.418	......	......
356	.12755	22.366	123.950	0.8892	.01423	6.387	82.96	3.292	2.927	2.362	8.964	......	......
357	.06910	22.195	66.000	0.5542	.00887	3.981	85.48	2.805	1.554	2.355	7.791	......	......
358	.03324	21.947	30.910	.3322	.00531	2.383	83.98	3.095	1.028	3.326	6.200	......	......

Series 6

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

Average Lift 11.40 feet

Average Submergence 40.97 per cent

Well Casing open to Atmosphere

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
359	.16245	20.205	118.600	.6603	.01056	4.739	40.36	11.522	7.608	6.415	15.384	....	....
360	.15727	20.040	112.020	.6584	.01053	4.726	40.36	11.522	7.586	6.773	14.934	....	....
361	.14641	19.735	99.620	.6904	.01105	4.959	41.12	11.376	7.853	7.883	13.251	....	....
362	.13339	19.393	85.770	.6714	.01074	4.820	40.43	11.509	7.727	9.009	12.419	....	....
363	.11566	19.045	69.870	.6801	.01088	4.883	41.11	11.378	7.738	11.075	10.630	....	....
364	.10565	18.821	61.410	.6879	.01101	4.941	40.90	11.419	7.854	12.790	9.596	....	....
365	.09236	18.609	51.420	.6819	.01091	4.896	40.84	11.430	7.794	15.156	8.465	....	....
366	.07979	18.421	42.718	.6911	.01106	4.964	41.04	11.392	7.873	18.432	7.215	....	....
367	.06059	18.108	30.240	.6700	.01072	4.811	41.10	11.380	7.624	25.212	5.652	....	....
368	.04214	18.020	20.630	.6307	.01009	4.528	41.38	11.326	7.144	34.637	4.177	....	....
369	.02258	17.943	10.795	.4668	.00747	3.353	42.06	11.194	5.225	48.402	3.023	....	....

Series 7

1¼ inch Harris Pump

Length of Eduction Pipe 19.32 feet

Average Lift 10.88 feet

Average Submergence 43.66 per cent

Supply of Compressed Air in Well Casing shut off from Air Main

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
370	.15286	20.153	110.730	.7500	.01200	5.386	43.36	10.943	8.208	7.411	12.738	....	....
371	.14442	19.988	102.250	.7566	.01211	5.435	43.50	10.916	8.259	8.077	11.926	....	....
372	.13800	19.818	95.200	.7533	.01205	5.408	43.50	10.916	8.223	8.638	11.453	....	....
373	.12812	19.602	83.840	.7627	.01220	5.475	43.63	10.891	8.306	9.907	10.503	....	....
374	.11721	19.333	73.180	.7646	.01223	5.489	43.63	10.891	8.327	11.379	9.584	....	....
375	.10433	19.118	62.750	.7695	.01231	5.525	43.63	10.891	8.380	13.355	8.474	....	....
376	.09344	18.924	54.160	.7702	.01232	5.529	43.76	10.866	8.369	15.452	7.585	....	....
377	.08294	18.753	46.535	.7715	.01234	5.538	43.76	10.866	8.382	18.015	6.722	....	....
378	.07054	18.559	37.980	.7707	.01233	5.534	43.69	10.879	8.384	22.076	5.722	....	....
379	.05435	18.376	28.142	.7407	.01185	5.318	43.69	10.879	8.058	28.632	4.587	....	....

SERIES 8

1¼ inch Harris Pump

Length of Eduction Pipe 26.74 feet

Average Lift 15.70 feet

Average Submergence 41.29 per cent

Well Casing open to Atmosphere

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
381	.02768	18.661	15.559	.3528	.00564	2.531	43.92	14.997	5.291	34.007	4.908	0.66	.3[illegible]54
383	.05711	19.363	36.595	.7094	.01135	5.094	40.76	15.842	11.238	30.710	5.032	....	....
384	.08941	19.770	61.190	.7340	.01174	5.269	40.76	15.842	11.628	19.005	7.617	1.38	.0943
385	.09389	19.858	65.140	.7377	.01180	5.296	40.76	15.842	11.687	17.942	7.957	1.39	.0917
386	.11082	20.135	80.280	.7278	.01164	5.225	40.76	15.842	11.530	14.363	9.520	1.37	.1058
387	.12442	20.424	94.540	.7451	.01192	5.349	41.16	15.735	11.724	12.402	10.438	1.40	.0779
388	.13729	20.683	107.980	.7423	.01188	5.333	41.16	15.735	11.680	10.818	11.557	....	....
389	.15024	21.013	123.230	.7396	.01183	5.309	41.16	15.735	11.638	9.444	12.700	1.39	.0700
390	.16155	21.267	136.950	.7374	.01180	5.297	41.16	15.735	11.603	8.473	13.689	1.39	.0667

Series 9

1¼ inch Harris Pump

Length of Eduction Pipe 26.74 feet

Average Lift 16.02 feet

Average Submergence 40.08 per cent

Supply of Compressed Air in Well Casing Connected with Air Main

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
391	.16016	19.557	107.040	.7180	.01149	5.157	37.73	16.652	11.955	11.168	13.939	....	....
392	.15329	19.557	102.420	0.7240	.01158	5.197	37.98	16.585	12.007	11.723	13.239	....	....
393	.13558	19.557	90.640	0.7443	.01191	5.345	38.70	16.392	12.201	13.461	11.384	....	....
394	.12313	19.695	84.150	0.7995	.01279	5.740	39.93	16.062	12.842	15.261	9.627	1.50	.0574
395	.10836	19.736	74.560	0.8229	.01316	5.906	40.57	15.892	13.078	17.540	8.234	1.55	.0671
396	.09476	19.689	64.770	0.7779	.01244	5.584	40.48	15.917	12.382	19.119	7.617	....	....
397	.08192	19.695	56.060	0.7592	.01215	5.453	41.31	15.695	11.914	21.252	6.743	1.43	.0951
398	.06941	19.677	47.337	0.7549	.01208	5.421	41.17	15.732	11.875	25.086	5.746	1.42	.1070
399	.03867	19.194	23.978	0.5848	.00936	4.201	41.37	15.678	9.168	38.236	4.131	....	....
400	.02735	19.170	17.127	0.4817	.00771	3.460	41.61	15.614	7.521	43.917	3.547	....	....

Series 10

1¼ inch Harris Pump

Length of Eduction Pipe 26.74 feet

Average Lift 15.73 feet

Average Submergence 41.19 per cent

Supply of Compressed Air in Well Casing Shut off from Air Main

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input. in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	q_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
401	.01865	19.022	11.537	0.3038	.00486	2.181	40.97	15.785	4.796	41.567	3.838	....	....
402	.04614	19.034	28.611	0.6384	.01021	4.582	39.63	16.143	10.306	36.025	4.519	1.20	.1434
403	.07618	19.553	51.610	0.7530	.01205	5.409	41.01	15.775	11.878	23.015	6.322	....	....
404	.08477	19.717	58.975	0.7474	.01196	5.368	41.12	15.745	11.768	19.955	7.089	1.40	.0956
405	.10125	19.925	72.620	0.7510	.01201	5.390	41.06	15.761	11.836	16.298	8.431	1.41	.0875
406	.11055	20.142	81.810	0.7530	.01205	5.408	41.27	15.706	11.827	14.456	9.175	....	....
407	.12091	20.360	92.140	0.7544	.01207	5.418	41.45	15.657	11.810	12.818	10.018	1.42	.0683
409	.14969	21.150	126.280	0.8007	.01281	5.749	42.99	15.245	12.207	9.667	11.684	....	....

Series 11

1¼ inch Harris Pump

Length of Eduction Pipe 26.74 feet

Average Lift 4.74 feet

Average Submergence 82.40 per cent

Supply of Compressed Air in Well Casing Shut off from Air Main

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, to pounds per square inch.	Input. in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
410	.02958	23.922	31.741	2.1421	.03427	15.382	82.35	4.738	10.148	31.970	0.863	....	....
411	.05231	24.058	46.750	2.3443	.03751	16.835	81.99	4.818	11.294	19.903	1.395	4.41	.0334
412	.06542	24.141	71.465	2.3288	.03726	16.723	81.99	4.818	11.219	15.698	1.756	....	....
413	.08416	24.388	93.740	2.3073	.03692	16.570	81.99	4.818	11.116	11.858	2.280	4.33	.0331
414	.10138	24.641	115.150	2.2683	.03629	16.287	82.38	4.713	10.691	9.284	2.794	....	....
415	.11222	24.771	128.770	2.2322	.03571	16.028	82.42	4.702	10.495	8.150	3.143	4.19	.0317
416	.11977	24.901	138.673	2.2166	.03546	15.916	82.42	4.702	10.422	7.516	3.378	....	....
417	.13375	25.137	157.680	2.1740	.03478	15.611	82.72	4.622	10.047	6.373	3.846	....	....
418	.14417	25.278	171.580	2.1475	.03436	15.422	82.58	4.659	10.004	5.831	4.196	4.03	.0294
419	.15856	25.550	192.480	2.0996	.03359	15.078	82.58	4.659	9.782	5.033	4.721	....	....
420	.16968	25.832	209.94[illegible]	2.0798	.03327	14.933	83.01	4.544	9.450	4.502	5.101	3.91	.0279

Series 12

1¼ inch Harris Pump

Length of Eduction Pipe 26.74 feet

Average Lift 4.48 feet

Average Submergence 83.26 per cent

Supply of Compressed Air in Well Casing Connected with Air Main

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
421	.16317	24.712	186.370	2.1658	.03465	15.553	82.49	4.683	10.142	5.442	4.709	....	....
422	.15415	24.741	176.400	2.1868	.03499	15.705	82.47	4.688	10.253	5.812	4.406	4.11	.0247
423	.14477	24.730	165.560	2.2125	.03540	15.889	82.47	4.688	10.372	6.265	4.090	....	....
424	.13803	24.844	159.990	2.2821	.03651	16.386	83.86	4.317	9.851	6.157	3.781	4.29	.0260
425	.13260	24.821	153.400	2.2855	.03657	16.413	83.90	4.307	9.843	6.417	3.626	....	....
426	.11900	24.791	137.400	2.3079	.03692	16.570	83.85	4.318	9.965	7.253	3.223	....	....
427	.11414	24.796	131.860	2.3125	.03700	16.606	84.00	4.279	9.895	7.504	3.085	4.35	.0299
428	.09308	24.608	106.060	2.3414	.03746	16.813	83.71	4.357	10.202	9.619	2.485	....	....
429	.06418	24.260	71.120	2.4001	.03840	17.235	83.51	4.410	10.584	14.882	1.671	4.51	.0323
430	.04296	23.942	46.425	2.2523	.03604	16.178	82.33	4.726	10.643	22.927	1.192	....	....

SERIES 13

1¼ inch Harris Pump

Length of Eduction Pipe 26.74 feet

Average Lift 4.79 feet

Average Submergence 82.23 per cent

7.5 feet of 2-inch Pipe at Upper End of Eduction Pipe

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction,
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
431	.04783	23.751	51.890	2.6378	.04220	18.941	81.70	4.895	12.911	24.883	1.134	......	......
432	.06223	23.857	68.090	2.6902	.04307	19.331	81.60	4.922	13.241	19.449	1.445	......	......
433	.07868	24.011	87.120	2.6972	.04315	19.367	81.60	4.922	13.274	15.237	1.824	......	......
434	.08575	24.175	96.240	2.7064	.04330	19.434	82.14	4.773	12.918	13.425	1.981	......	......
435	.09630	24.305	109.170	2.6881	.04301	19.303	82.14	4.773	12.830	11.753	2.239	......	......
436	.10791	24.500	124.140	2.6668	.04267	19.153	82.44	4.698	12.528	10.092	2.529	......	......
437	.11888	24.706	138.920	2.6265	.04202	18.859	82.68	4.632	12.165	8.756	2.829	......	......
438	.12994	24.883	153.870	2.6145	.04183	18.775	82.68	4.632	12.109	7.869	3.106	......	......
439	.14444	25.137	174.020	2.5808	.04129	18.532	82.68	4.632	11.952	6.869	3.498	......	......
440	.15295	25.390	187.650	2.5544	.04087	18.343	82.68	4.632	11.832	6.306	3.743	......	......

Series 14

1¼ inch Harris Pump

Length of Eduction Pipe 41.50 feet

Average Lift 7.66 feet

Average Submergence 81.54 per cent

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
441	.04628	29.119	68.780	2.6318	.04211	18.900	81.57	7.650	20.132	29.270	1.099	....	....
442	.05673	29.160	84.550	2.7047	.04327	19.421	81.53	7.670	20.743	24.532	1.311	....	....
443	.07710	29.030	114.120	2.7174	.04348	19.515	80.24	8.200	22.281	19.525	1.773	....	....
444	.09321	29.431	140.730	2.7895	.04463	20.032	81.71	7.590	21.171	15.043	2.089	....	....
445	.11178	29.656	170.630	2.7721	.04435	19.905	81.68	7.602	21.073	12.350	2.520	....	....
446	.12360	29.786	189.750	2.7549	.04408	19.784	81.68	7.602	20.940	11.035	2.804	....	....
447	.13504	29.974	209.100	2.7230	.04356	19.551	81.68	7.602	20.700	9.899	3.100	5.12	.0184
448	.15065	30.268	236.490	2.6775	.04284	19.228	81.68	7.602	20.353	8.607	3.517	5.02	.0166
449	.16503	30.374	260.350	2.6510	.04241	19.033	81.68	7.602	20.153	7.741	3.892	4.98	.0173
450	.17810	30.598	283.800	2.6162	.04186	18.788	81.96	7.487	19.588	6.902	4.255	4.91	.0217

SERIES 15

1¼ inch Harris Pump

Length of Eduction Pipe 41.50 feet

Average Lift 23.47 feet

Average Submergence 43.45 per cent

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
452	.04608	22.184	41.703	0.7579	.01213	5.445	41.99	24.075	18.245	43.755	3.799	1.43	.1001
453	.06119	22.260	55.850	0.8763	.01402	6.292	41.88	24.121	21.138	37.850	4.365	1.65	.0745
454	.09139	22.906	89.060	1.0502	.01680	7.540	42.67	23.793	24.984	28.052	5.441	1.97	.0506
455	.11442	23.259	114.990	1.0613	.01698	7.621	43.68	23.372	24.808	21.573	6.739	1.99	.0462
456	.13427	23.536	138.320	1.0515	.01682	7.549	43.75	23.345	24.548	17.745	7.983	1.98	.0431
457	.14235	23.814	150.900	1.0752	.01720	7.719	43.97	23.252	25.001	16.567	8.276	2.02	.0414
458	.14586	23.897	155.720	1.0732	.01717	7.706	44.13	23.187	24.882	15.979	8.495	2.02	.0410
459	.15958	24.120	173.410	1.0652	.01704	7.647	44.19	23.161	24.670	14.227	9.365	2.00	.0391
460	.17384	24.350	192.570	1.0468	.01675	7.518	44.82	22.900	23.970	12.447	10.389	1.98	.0378

Series 16

1¼ inch Indiana Pump

Length of Eduction Pipe 42.08 feet

Average Lift 24.20 feet

Average Submergence 42.50 per cent

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
461	.06385	22.504	61.980	0.9346	.01495	6.710	42.78	24.079	22.504	36.308	4.272	....	....
462	.08435	22.734	83.580	1.0533	.01685	7.563	42.40	24.239	25.525	30.540	5.006	....	....
463	.10107	22.893	101.700	1.0839	.01734	7.782	42.25	24.304	26.342	25.903	5.829	....	....
464	.11530	23.135	118.660	1.0359	.01737	7.795	42.41	24.236	26.318	22.178	6.638	....	....
465	.13223	23.447	139.650	1.0842	.01735	7.787	42.19	24.327	26.375	18.837	7.022	....	....
466	.03937	22.562	38.830	0.6931	.01109	4.977	43.56	23.753	16.462	42.400	3.550	....	....
467	.05899	22.556	58.300	0.9791	.01566	7.028	42.79	24.077	23.573	40.435	3.767	....	....
468	.08997	22.775	90.630	1.1111	.01778	7.980	42.22	24.313	27.013	29.807	5.000	....	....
469	.12171	23.346	128.870	1.1309	.01809	8.119	42.16	24.340	27.527	21.360	6.728	....	....
470	.16194	24.236	184.150	0.9761	.01562	7.010	42.25	24.313	23.730	12.886	10.368	....	....

SERIES 17

1¼ inch Indiana Pump

Length of Eduction Pipe 42.08 feet

Average Lift 7.63 feet

Average Submergence 81.95 per cent

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Imput, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
471	.02344	29.439	35.582	1.4842	.02375	10.659	81.48	7.797	11.573	32.525	0.987	....	....
472	.05683	29.514	86.570	2.7549	.04407	19.780	81.48	7.797	21.480	24.814	1.290	....	....
473	.06171	29.657	94.610	2.9091	.04655	20.893	81.48	7.797	22.682	23.975	1.326	....	....
474	.04650	29.568	71.010	2.6282	.04205	18.873	81.88	7.627	20.045	28.230	1.106	....	....
475	.09030	29.875	139.820	3.0043	.04807	21.574	81.81	7.653	22.993	16.445	1.879	....	....
476	.11778	30.179	185.180	3.0259	.04841	21.727	81.82	7.652	23.153	12.503	2.433	....	....
477	.14039	30.497	223.820	3.0078	.04812	21.597	83.07	7.127	21.435	9.577	2.918	....	....
478	.15713	30.545	251.080	2.9306	.04689	21.046	81.98	7.587	22.235	8.855	3.352	....	....
479	.16622	30.639	266.750	2.8738	.04598	20.638	81.53	7.771	22.330	8.371	3.615	....	....
480	.17769	30.957	289.040	2.8758	.04601	20.650	83.00	7.533	21.661	7.494	3.862	....	....

SERIES 18

1¼ inch Tee Pump

Length of Eduction Pipe 41.60 feet

Average Lift 6.58 feet

Average Submergence 84.18 per cent

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Imput, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
481	.02299	29.628	34.903	1.9931	.03189	14.313	84.28	6.540	13.034	37.345	0.721	....	....
482	.05188	29.598	78.650	2.6369	.04219	18.937	84.11	6.605	17.417	22.146	1.230	....	....
483	.08346	29.573	126.380	3.0145	.04823	21.648	83.71	6.777	20.427	16.163	1.730	....	....
484	.09323	29.739	142.220	3.1033	.04965	22.283	84.28	6.540	20.295	14.270	1.878	....	....
485	.11101	29.792	169.760	3.1251	.05000	22.441	84.01	6.645	20.765	12.232	2.220	....	....
486	.12285	29.898	188.850	3.1300	.05008	22.478	84.30	6.529	20.435	10.821	2.453	....	....
487	.12708	29.969	196.050	3.1373	.05020	22.532	84.28	6.542	20.524	10.469	2.532	....	....
488	.13555	30.033	209.630	3.1325	.05011	22.491	84.18	6.580	20.610	9.832	2.705	....	....
489	.14628	30.092	226.750	3.1325	.05011	22.491	84.26	6.556	20.535	9.056	2.920	....	....
490	.15770	29.757	239.990	3.0489	.04878	21.893	84.40	6.487	19.777	8.240	3.194	....	....

SERIES 19

1¼ inch Tee Pump

Length of Eduction Pipe 41.60 feet

Average Lift 23.96 feet

Average Submergence 42.40 per cent

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tall piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{g_w}$	v_i	c_p
491	.03234	21.930	30.072	0.6857	.01097	4.924	42.74	23.823	16.333	54.307	2.948	....	....
492	.05557	21.912	51.610	0.8762	.01402	6.292	42.48	23.929	20.965	40.620	3.964	....	....
493	.08162	22.083	77.170	1.0500	.01680	7.540	42.62	23.870	25.063	32.480	4.859	....	....
494	.10163	22.255	97.700	1.0883	.01741	7.813	42.07	24.103	26.230	26.847	5.838	....	....
495	.12077	22.384	117.600	1.0839	.01734	7.782	42.36	23.978	25.990	22.101	6.965	....	....
496	.13632	22.567	135.350	1.0817	.01731	7.769	42.39	23.965	25.920	19.150	7.876	....	....
497	.14213	22.673	142.200	1.0808	.01729	7.759	42.33	23.993	25.930	18.235	8.221	....	....
498	.15487	22.797	156.960	1.0742	.01719	7.715	42.33	23.992	25.771	16.419	9.009	....	....
499	.16434	22.879	167.800	1.0635	.01701	7.635	42.26	24.021	25.548	15.225	9.662	....	....
500	.17430	23.032	180.380	1.0552	.01688	7.576	42.46	23.939	25.260	14.004	10.326	....	....

Series 20

1¼ inch Tee Pump

Variable Length of Eduction Pipe

Constant Lift of Five feet

Variable Submergence

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q}{q_w}$	v_i	c_p
501	.17902	16.433	60.830	0.3049	.00488	2.190	30.00	5.00	1.524	2.510	37.968	....	....
502	.16960	16.350	55.700	0.3125	.00500	2.244	30.00	"	1.562	2.802	33.920	....	....
503	.16610	16.244	52.325	0.3012	.00485	2.177	30.00	"	1.506	2.878	34.251	....	....
504	.15602	16.091	45.873	0.3044	.00482	2.163	30.00	"	1.522	3.318	32.372	....	....
505	.14962	16.047	43.429	0.3077	.00492	2.208	30.00	"	1.538	3.543	30.412	....	....
506	.12849	15.820	33.365	0.2950	.00472	2.118	30.00	"	1.475	4.421	27.224	....	....
507	.11937	15.649	28.262	0.2755	.00441	1.979	30.00	"	1.387	4.910	27.068	....	....
508	.11257	15.407	23.040	0.2294	.00367	1.647	30.00	"	1.147	4.978	30.670	....	....
509	.07932	15.284	14.843	0.1887	.00302	1.355	30.00	"	0.943	6.357	26.267	....	....
510	.17903	16.826	60.830	0.3192	.00511	2.293	30.00	"	1.596	2.624	35.040	....	....
511	.12482	16.690	40.513	0.3178	.00508	2.280	30.00	"	1.589	3.920	24.574	....	....
512	.14870	16.412	42.588	0.2960	.00474	2.127	30.00	"	1.480	3.475	31.372	....	....
513	.10607	15.948	24.097	0.2650	.00424	1.903	30.00	"	1.325	5.500	25.017	....	....
514	.08495	15.694	16.548	0.2142	.00343	1.539	30.00	"	1.071	6.470	24.768	....	....
515	.06883	15.586	12.361	0.1686	.00270	0.990	30.00	"	0.843	6.280	47.800	....	....
516	.08477	30.620	134.890	3.5600	.05700	25.583	88.00	"	17.800	13.220	1.487	....	....
517	.16847	31.551	278.850	3.5100	.05620	25.224	88.00	"	17.550	6.295	2.998	....	....
518	.16530	31.544	273.600	3.5350	.05660	25.403	88.00	"	17.675	6.465	2.921	....	....
519	.15052	31.364	247.140	3.5880	.05740	25.760	88.00	"	17.440	7.065	2.622	....	....
520	.12154	30.898	195.670	3.6000	.05760	25.850	88.00	"	18.000	9.210	2.110	....	....

Series 20—Continued

1¼ inch Tee Pump

Variable Length of Eduction Pipe

Constant Lift of Five feet

Variable Submergence

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
521	.09058	30.628	144.220	3.5350	.05660	25.403	88.00	5.00	17.675	12.222	1.601	....	....
522	.07174	30.463	113.400	3.4220	.05480	24.596	88.00	”	17.110	15.100	1.309	....	....
523	.05023	30.365	79.020	3.1620	.05070	22.756	88.00	”	15.810	20.150	0.991	....	....
524	.04619	30.365	72.660	3.0940	.04950	22.170	88.00	”	15.470	21.280	0.933	....	....
525	.03906	30.316	61.373	2.9400	.04700	21.095	88.00	”	14.700	23.980	0.831	....	....
526	.05982	30.463	94.560	3.3100	.05300	23.788	88.00	”	16.550	17.500	1.129	....	....
527	.07484	30.537	118.590	3.4600	.05540	24.867	88.00	”	17.300	14.600	1.351	....	....
528	.09855	30.761	157.850	3.2380	.05180	23.250	88.00	”	16.190	10.270	1.903	....	....
529	.13623	31.151	221.870	3.2640	.05230	23.473	88.00	”	16.320	8.070	2.605	....	....
530	.13872	23.941	149.380	2.5910	.04152	18.637	80.00	”	12.955	8.672	3.341	....	....
531	.13235	23.888	142.510	2.6112	.04185	18.784	80.00	”	13.056	9.161	3.163	....	....
532	.13120	23.862	140.300	2.6180	.04196	18.832	80.00	”	13.090	9.330	3.127	....	....
533	.12688	23.771	134.450	2.6387	.04229	18.980	80.00	”	13.194	9.815	3.001	....	....
534	.11800	23.713	124.500	2.6387	.04229	18.980	80.00	”	13.194	10.600	2.790	....	....
535	.10855	23.587	113.160	2.6457	.04240	19.030	80.00	”	13.228	11.690	2.560	....	....
536	.09870	23.507	102.330	2.6528	.04251	19.082	80.00	”	13.264	12.962	2.322	....	....
537	.09180	23.458	94.650	2.6528	.04251	19.082	80.00	”	13.264	14.014	2.159	....	....
538	.08328	23.385	85.380	2.6457	.04240	19.030	80.00	”	13.228	15.492	1.964	....	....
539	.07144	23.295	72.700	2.6180	.04196	18.831	80.00	”	13.090	18.008	1.703	....	....
540	.06130	23.225	62.020	2.5511	.04089	18.352	80.00	”	12.755	20.575	1.499	....	....

SERIES 20—Continued

1¼ inch Tee Pump

Variable Length of Eduction Pipe

Constant Lift of Five feet

Variable Submergence

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
541	.04929	23.157	49.520	1.9610	.03143	14.104	80.00	5.00	9.805	19.805	1.568	....	....
542	.03443	23.092	34.380	2.2222	.03562	15.984	80.00	”	11.111	32.323	0.967	....	....
543	.04877	23.128	48.920	2.4040	.03849	17.278	80.00	”	12.020	24.575	1.267	....	....
544	.16384	24.281	181.110	2.5643	.04110	18.447	80.00	”	12.822	7.080	3.987	....	....
545	.15805	20.577	124.330	1.8293	.02932	13.155	70.00	”	9.146	7.357	5.392	....	....
546	.14968	20.446	116.010	1.8422	.02952	13.250	70.00	”	9.211	7.941	5.070	....	....
547	.14369	20.363	110.010	1.8383	.02946	13.221	70.00	”	9.191	8.356	4.877	....	....
548	.13967	20.283	105.810	1.8383	.02946	13.221	70.00	”	9.191	8.688	4.741	....	....
549	.13330	20.202	99.820	1.8383	.02946	13.221	70.00	”	9.191	9.210	4.525	....	....
550	.10339	20.092	76.200	1.8658	.02990	13.418	70.00	”	9.329	12.243	3.458	....	....
551	.11514	20.013	83.980	1.8728	.03001	13.470	70.00	”	9.364	11.150	3.837	....	....
552	.10590	19.889	75.780	1.8658	.02990	13.418	70.00	”	9.329	12.310	3.542	....	....
553	.09700	19.797	68.520	1.8728	.03001	13.470	70.00	”	9.364	13.670	3.232	....	....
554	.08380	19.661	57.910	1.8728	.03001	13.470	70.00	”	9.364	16.170	2.792	....	....
555	.07253	19.595	49.630	1.8451	.02957	13.257	70.00	“	9.225	18.590	2.453	....	....
556	.05421	19.500	36.510	1.7986	.02882	12.935	70.00	“	8.993	24.630	1.881	....	....
557	.06866	19.583	46.930	1.8451	.02957	13.244	70.00	“	9.225	19.670	2.322	....	....
558	.02937	20.416	22.650	1.4750	.02364	10.610	70.00	“	7.375	32.560	1.242	....	....
559	.15917	19.480	108.300	1.5580	.02497	11.208	65.00	“	7.790	7.192	6.376	....	....
560	.15302	19.383	102.250	1.5480	.02481	11.136	65.00	“	7.740	7.570	6.168	....	....

Series 20—Continued

1¼ inch Tee Pump

Variable Length of Eduction Pipe

Constant Lift of Five feet

Variable Submergence

1	2	3	4	5	6	7	8	9	10	11	12	3	14
Number of run.	Quantity of free air in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
561	.14462	19.244	94.430	1.5530	.02489	11.172	65.00	5.00	7.765	8.234	5.810	....	....
562	.13850	19.178	89.460	1.5770	.02528	11.347	65.00	"	7.885	8.814	5.480	....	....
563	.12730	19.028	80.220	1.5770	.02528	11.347	65.00	"	7.885	9.828	5.036	....	....
564	.11986	18.906	73.680	1.5720	.02519	11.306	65.00	"	7.860	10.670	4.760	....	....
565	.10973	18.791	66.200	1.5770	.02528	11.347	65.00	"	7.885	11.912	4.342	....	....
566	.10100	18.676	59.620	1.5820	.02535	11.378	65.00	"	7.910	13.268	3.984	....	....
567	.09206	18.585	53.440	1.5970	.02559	11.486	65.00	"	7.985	14.942	3.598	....	....
568	.07798	18.433	43.780	1.5770	.02528	11.347	65.00	"	7.885	18.010	3.019	....	....
569	.06224	18.299	33.980	1.5430	.02473	11.100	65.00	"	7.715	22.702	2.517	....	....
570	.04100	18.212	22.080	1.4620	.02343	10.516	65.00	"	7.310	33.107	1.750	....	....
571	.02666	18.131	14.047	1.2340	.01978	8.869	65.00	"	6.170	43.950	0.634	....	....
572	.14218	18.708	81.440	1.2820	.02053	9.214	60.00	"	6.410	7.871	6.926	....	....
573	.14089	18.649	79.890	1.2920	.02070	9.290	60.00	"	6.400	8.087	6.807	....	....
574	.14441	18.605	80.900	1.2920	.02070	9.290	60.00	"	6.460	7.985	6.977	....	....
575	.13696	18.555	76.090	1.2765	.02045	9.178	60.00	"	6.382	8.388	6.697	....	....
576	.12870	18.454	70.030	1.2887	.02065	9.267	60.00	"	6.443	9.201	6.233	....	....
577	.12064	18.343	64.270	1.3020	.02086	9.362	60.00	"	6.510	10.130	5.784	....	....
578	.10852	18.201	55.940	1.3160	.02110	9.470	60.00	"	6.580	11.763	5.144	....	....
579	.09120	18.013	44.940	1.2903	.02068	9.281	60.00	"	6.451	14.356	4.410	....	....
580	.07681	17.865	36.530	1.2820	.02055	9.223	60.00	"	6.410	17.550	3.738	....	....

SERIES 20—Continued

1¼ inch Tee Pump

Variable Length of Eduction Pipe

Constant Lift of Five feet

Variable Submergence

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air, in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
581	.06479	17.742	29.810	1.2500	.02003	8.990	60.00	5.00	6.250	20.968	3.235	....	....
582	.04248	17.624	18.980	1.1363	.01821	8.173	60.00	”	5.681	29.935	2.333	....	....
583	.03024	17.005	11.250	0.9757	.01563	7.015	60.00	”	4.878	43.365	1.935	....	....
584	.15900	17.896	74.070	0.8870	.01422	6.382	50.00	”	4.435	5.994	11.180	....	....
585	.16970	17.997	81.000	0.8811	.01412	6.337	50.00	”	4.405	5.386	12.020	....	....
586	.15541	17.789	70.630	0.8870	.01422	6.382	50.00	”	4.435	6.280	10.930	....	....
587	.14218	17.679	62.440	0.8870	.01422	6.382	50.00	”	4.435	7.103	9.990	....	....
588	.13527	17.563	57.330	0.8811	.01412	6.337	50.00	”	4.405	7.684	9.586	....	....
589	.12915	17.434	52.970	0.8788	.01408	6.319	50.00	”	4.394	7.840	9.174	....	....
590	.11692	17.308	45.990	0.8646	.01386	6.220	50.00	”	4.323	9.390	8.439	....	....
591	.10560	17.196	40.300	0.8824	.01414	6.346	50.00	”	4.412	10.940	7.482	....	....
592	.08915	17.003	32.000	0.8427	.01351	6.064	50.00	”	4.213	13.170	6.236	....	....
593	.07646	16.905	26.010	0.8310	.01332	5.978	50.00	”	4.155	15.900	5.740	....	....
594	.05662	16.806	18.810	0.7834	.01256	5.637	50.00	”	3.917	20.820	4.580	....	....
595	.02661	16.632	8.270	0.5376	.00862	3.867	50.00	”	2.688	32.500	3.089	....	....
596	.15290	17.075	59.550	0.5731	.00918	4.120	40.00	”	2.865	4.814	16.655	....	....
597	.14323	16.922	53.330	0.5556	.00890	3.995	40.00	”	2.778	5.209	16.094	....	....
598	.14001	16.898	51.590	0.5556	.00890	3.995	40.00	”	2.778	5.385	15.731	....	....
599	.13358	16.773	48.710	0.5510	.00883	3.963	40.00	”	2.755	5.656	15.128	....	....
600	.13065	16.733	45.400	0.5495	.00881	3.954	40.00	”	2.747	6.053	14.830	....	....

Series 20—Continued

1¼ inch Tee Pump

Variable Length of Eduction Pipe

Constant Lift of Five feet

Variable Submergence

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Number of run.	Quantity of free air in cubic feet per second.	Absolute pressure of air at gage, in pounds per square inch.	Input, in foot pounds per second.	Discharge of water, in pounds per second.	Discharge of water, in cubic feet per second.	Discharge of water, in gallons per minute.	Submergence, in per cent.	Lift, in feet.	Output, in foot pounds per second.	Efficiency, in per cent.	Ratio of volume of air to volume of water.	Velocity of water in a 1¼ in. tail piece.	Coefficient of slip and pipe friction.
	q_a	p_g	l_i	w_w	q_w	q_g	s	h_l	l_o	e	$\frac{q_a}{q_w}$	v_i	c_p
601	.12152	16.588	39.910	0.5450	.00873	3.918	40.00	"	2.725	6.828	13.920	....	....
602	.11320	16.450	35.660	0.5391	.00864	3.878	40.00	"	2.695	7.559	13.102	....	....
603	.09990	16.356	29.760	0.5319	.00852	3.824	40.00	"	2.659	8.936	11.727	....	....
604	.08929	16.205	24.890	0.4914	.00788	3.536	40.00	"	2.457	9.871	11.330	....	....
605	.07830	16.107	20.930	0.4762	.00763	3.424	40.00	"	2.381	11.375	10.263	....	....
606	.06226	15.994	15.690	0.4386	.00703	3.155	40.00	"	2.193	13.980	8.856	....	....
607	.05360	15.864	12.590	0.3704	.00594	2.666	40.00	"	1.852	14.710	9.320	....	....
608	.03978	15.796	8.960	0.3058	.00490	2.199	40.00	"	1.529	17.065	8.119	....	....

TABLE II

LOSS DUE TO FRICTION IN AIR PIPE AND NOZZLE WHEN DISCHARGING INTO THE ATMOSPHERE

Series I

Run.	Quantity of free air in cubic feet per second.	Loss of head in pounds per square inch.
279	.13253	.658
280	.14018	.750
281	.12336	.585
282	.11439	.490
283	.09530	.355
284	.10438	.416
285	.07792	.225
286	.08059	.238
287	.08597	.282
288	.07052	.208
289	.06264	.160
290	.07025	.186
291	.05847	.126
292	.04926	.091
293	.05392	.117
294	.04071	.061
295	.03697	.004
296	.01951	.001

TABLE III

LOSS DUE TO FRICTION IN AIR PIPE AND NOZZLE WHEN DISCHARGING INTO THE ATMOSPHERE

Series 2–13 inclusive

Run.	Quantity of free air in cubic feet per second.	Loss of head in pounds per square inch.
1	.05860	0.4185
2	.07510	0.6424
3	.09098	0.9490
4	.11035	1.3556
5	.12047	1.6090
6	.12978	1.8095
7	.13847	2.0924
8	.14710	2.2986
9	.15367	2.4695
10	.16303	2.8527

TABLE IV

LOSS DUE TO FRICTION IN AIR PIPE AND NOZZLE WHEN DISCHARGING INTO THE ATMOSPHERE

Series 14 and 15

Run.	Quantity of free air in cubic feet per second.	Loss of head in pounds per square inch.
1	.02347	0.0825
2	.04092	0.2358
3	.07531	0.6071
4	.09119	0.8605
5	.10425	1.1022
6	.11822	1.4086
7	.13095	1.6621
8	.14068	1.9215
9	.15153	2.1750
10	.16493	2.5521

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